APPENDIX D
MODELING STREAMFLOW AND WATER TEMPERATURE IN THE BIG HOLE RIVER, MONTANA - 2006

Modeling Streamflow and Water Temperature in the Big Hole River, Montana – 2006

K. Flynn, D. Kron, M. Granger
TMDL Technical Report DMS-2008-03

Front Cover: Big Hole River above the confluence with the Jefferson River

Image courtesy of: Big Sky Fishing.Com; http://www.bigskyfishing.com

Other Credits:

Outreach and landowner coordination: Big Hole River Watershed Committee
Field data collection: Watershed Consulting, Inc.

EXECUTIVE SUMMARY

The one-dimensional, dynamic water quality model Heatsource v7.0 was applied to the Big Hole River in southwestern Montana to evaluate stream temperature improvement scenarios for a 152.5 kilometer reach extending from approximately Wisdom to the confluence with the Beaverhead River near Twin Bridges. This reach has been identified as a primary concern due to elevated summer temperatures, low late-season flows, and the presence of Arctic grayling. An extensive field investigation was completed during summer 2006 to support the modeling. This included measurement of streamflow and water temperature at 20 Big Hole River main-stem locations, 44 tributaries and irrigation return flows, and 33 irrigation withdrawls.

Characterization of river hydraulics, measurement of stream shade, and continuous monitoring of climate were also completed. Results of predictive modeling suggest that the Big Hole River is impaired due to management activities, and that decreases of 0.13 and 0.59ºC (0.23 and 1.06ºF) in average and maximum temperatures could be achieved per implementation of “all reasonable soil and water conservation practices” (ARM 17.30.602). Temperatures would be 0.69 and 2.76ºC (1.24 and 4.97ºF) cooler under natural conditions. Through analysis of shade, geomorphology, and in-stream flow conditions, it was shown that flow alteration is the most significant contributor to warming of river, and subsequently, the most feasible alternative for returning the Big Hole to a more natural thermal regime. This of course, would require decreases in consumptive use either through irrigation efficiency improvements, or decreases in domestic water withdrawl. Finally, a unique condition was identified near the center of the watershed where significant groundwater influx and topographic shading result in thermal “resetting” of in-stream water temperatures. This functionally separates the upper and lower Big Hole River TMDL planning areas, and will allow for future management of the river as two distinct segments. This work has been initiated by Montana by Montana Department of Environmental Quality as part of the Total Maximum Daily Load (TMDL) program.

TABLE OF CONTENTS

FIGURES

TABLE OF TABLES

.

Conversion Factors and Datum

1 meter = 3.2808 feet
1 cubic meter per second (cms) = 35.313 cubic feet per second (cfs)
1 kilometer = 0.622 miles
1 square kilometer = 0.386 square miles

ACRONYMS

7Davg	7-day mean temperature
7Dmax	7-day maximum temperature
7Dmin	7-day minimum temperature
7Q5	7-day 5-year low flow
ARM	Administrative Rules of Montana
BHWC	Big Hole River Watershed Committee
BLM	Bureau of Land Management
BMPs	Best Management Practices
ºC	Degrees Celsius
COOP	Cooperative Observer
CWA	Clean Water Act
cfs	cubic feet per second
cms	cubic meters per second
CWAIC	Clean Water Act Information Center
DEM	Digital Elevation Model
DEQ	Montana Department of Environmental Quality
EPA	Environmental Protection Agency
ESA	Endangered Species Act
ET	Evapotranspiration
ºF	Degrees Fahrenheit
FWP	Montana Fish, Wildlife, and Parks
FY	Fiscal Year
GIS	Geographic Information System
HUC	Hydrologic Unit Code
LULC	Land Use/Land Cover
LSWCP	Land, Soil, and Water Conservation Practices
NAD83	National Accumulation of Datum - 1983
NAIP	National Agricultural Imagery Program
NAVD88	National Accumulation of Vertical Datum - 1988
NED	National Elevation Dataset
NHD	National Hydrography Dataset
NIST	National Institute of Standards and Technology
NLDC	National Land Cover Dataset
NOAA	National Oceanic and Atmospheric Administration
NPS	Nonpoint Source
NRCS	Natural Resources Conservation Service
NSE	Nash-Sutcliffe Coefficient of Efficiency
PBIAS	Percent Bias
QA	Quality Assurance
RAWS	Remote Automated Weather Station
SSR	Sum of Squared Residuals
SSTEMP	Stream Segment Temperature Model
TMDL	Total Maximum Daily Load
Tavg	Mean daily water temperature

Tmax	Maximum daily water temperature
Tmin	Minimum daily water temperature
TPA	TMDL Planning Area
UILT	Upper incipient lethal limit
USFWS	U.S. Fish and Wildlife Service
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
WRCC	Western Regional Climate Center
WRS	Water Resource Surveys

BACKGROUND

Conflicting demands between irrigated agriculture, anglers, and aquatic species have long been an issue in the arid west (Thomas and Anderson, 1976; Anderson, 1982; Pimentel et al, 1997; Pringle, 2000). The Big Hole River in southwestern Montana is no different, and mounting evidence suggests that low flow conditions and extensive dewatering have elevated summer water temperatures such that beneficial uses of the water body are impaired (CWAIC, 2006). As a result, Montana Department of Environmental Quality (DEQ) has commissioned a water temperature study such that the mechanistic relationship between in-stream water temperature, stream morphology, riparian conditions, and associated water management practices can be established for the summer critical low-flow period. Specifically, the one-dimensional, dynamic stream water quality model Heatsource v7.0 (Boyd and Kasper, 2004) was applied to a 152.5 kilometer reach extending from approximately Wisdom to the confluence with the Beaverhead River near Twin Bridges to evaluate irrigation improvement efficiencies and associated scenarios as part of the Total Maximum Daily Load (TMDL) program. This reach has been identified as a primary concern due to elevated summer temperatures, low late-season flows, and the presence of the last remaining native population of river-dwelling Arctic grayling in the lower 48 states (Magee et al., 2006; Rens and Magee, 2007). Subsequent analysis was also completed for a 94.5-km reach upstream of the project site using SSTEMP (Barthalow, 1989) to evaluate potential changes in headwater boundary conditions from upstream management activities.

Prior Studies

The Big Hole River has long been a concern in regard to elevated water temperatures and aquatic species. Lohr et al. (1996) documented fish kills in July of 1994 as water temperatures reached the upper incipient lethal limit (UILT) for Arctic Grayling of 25ºC (77ºF). Again, in 2002 and 2003, Magee and Lamothe (2003, 2004) recorded in-stream temperatures well above the UILT. Maximum values those years exceeded 27ºC (80.8ºF) and 26ºC (80.1ºF) respectively. The temporal duration of these impairments has been well characterized. According to the Big Hole River Watershed Committee (2000), threshold daily water temperature near the center of the watershed (e.g. the USGS gage near Melrose) has exceeded the indicator target of 21.1ºC (70ºF) at least once every year since 1977 while the 7-day average daily maximum temperature [7Dmax; e.g. 20ºC (68ºF)] has been exceeded 19 out of 22 years. Temperatures have been shown to be elevated in the lower reaches as well, with large longitudinal gradients extending as far downstream as Twin Bridges (Gammons et al., 2001). Significant surface water withdrawl has been cited as the greatest threat to the fishery (FWP 1989). As such, Montana Fish, Wildlife, and Parks (FWP) has characterized the river as chronically dewatered from approximately Glen to the confluence with the Jefferson River, and periodically throughout much of the rest of the watershed (MFISH 2007). Persistent drought has exacerbated effects of water use such that FWP has requested several year-round flow reservations to minimize the extent of withdrawl during the critical flow period (Rens and Magee, 2007). In addition to these preventative measures, the Big Hole River Drought Management Plan has been drafted to address voluntary water conservation and fishing closures in the basin. Currently, there are three triggers that result in fishing closures on the river (BHWC 2000): (1) when river temperatures exceed 21.1ºC (70ºF) for over 8 hours per day for three consecutive days, (2) when flows fall below 2.8 cms (100 cfs) at the USGS Mudd Creek gage, or (3) when flows are less than 7.1 cms (250 cfs) at the Melrose gage. In addition to these efforts, ongoing conservation projects have been implemented to improve streamflow, protect the function of streams and riparian habitats, and identify and eliminate threats to grayling (Rens and Magee, 2007). Thus, some action has already been taken to mitigate the symptoms of the temperature impairment in the basin. However, DEQ wishes to evaluate river corridor management scenarios such that cumulative effects of these activities on in-stream temperature can be identified. The goal of this study is to identify whether a suite of best management practices (BMPs) can be implemented in the river corridor such that the Montana steam temperature standard is attained and maintained (ARM 17.30.623).

Montana Temperature Standard (ARM 17.30.623)

Montana's in-stream temperature standard was originally developed to address point source discharges and therefore is difficult to interpret for non-point sources without use of water quality models. This is especially true when attempting to characterize departure from "natural occurring" conditions which effectively reflects the implementation of "all reasonable soil and water conservation practices" (ARM 17.30.602). As currently written, a maximum allowable increase of 0.55ºC (1ºF) over "naturally occurring" is acceptable for B-1 waters when natural temperatures are within the range of 0ºC to 18.9 ºC (32ºF to 66ºF). For temperatures 19.2 ºC (66.5ºF) or greater, a 0.23ºC (0.5ºF) increase is allowed (ARM 17.30.623 (2)(e)). Monitoring and modeling has been structured such that the existing temperature regime can be adequately addressed along with the expected temperatures from implementation of BMP improvements.

STUDY AREA

The Big Hole River drains approximately 7,250-km2 (2,800-mi2) of high- and mid-elevation mountainous topography in southwestern Montana. Originating from the continental divide, the river flows 247-km past the towns of Jackson, Wisdom, Wise River, Melrose, and Glen before reaching its endpoint near Twin Bridges. The entire watershed is part of United States Geological Survey (USGS) Hydrologic Unit Code (HUC) 10020004 and consists of predominantly of wide alluvial valleys that are constrained at a number of locations by narrowing geological outcrops. Currently, 242.5 km (150.7 miles) of the mainstem are listed as impaired for thermal modification (CWAIC, 2006). Given the size of the watershed, the study area has been broken into three distinct planning segments: (1) the upper TMDL planning area (TPA) which extends from the headwaters to Pintlar Creek, (2) middle TPA which extends from Pintlar Creek to Divide Creek (near Wisdom and Melrose respectively), and (3) the lower TPA which extends from Divide Creek to the confluence with the Beaverhead River. The DEQ study is focused primarily on the lower two TPA's extending from Pintlar Creek to the confluence with the Beaverhead River. The project site is most easily accessed via I-15 between Butte and Dillon, Highway-141 between Melrose and Wisdom, and on Burma Road between Glen and Twin Bridges (**fig D-1**).

Climate

Climate in the Big Hole River watershed is inter-montane continental, with marked seasonality (**fig. D-2a**). Cooperative observation station Divide 2 NW (COOP ID 242421) indicates that average temperatures during 1971-2000 range from 25 to 30°C in the summer months to as low as -10°C in the winter (WRCC, 2007). July and August are the warmest months of the year, and are influenced by Pacific high pressure systems that cause long periods of warm and dry weather. Clear skies and warm days prevail during these months. Because of the high elevation of the watershed, the diurnal variation in temperature is often greater that other areas of Montana, characteristic of warm days and cool nights (Deer Lodge WRS, 1955). Average precipitation in the watershed ranges from 250-300 mm (10-12 inches) in the valleys to over 1,000 mm (50 inches) in the mountains (Marvin and Voller, 2000). Most of this precipitation occurs during the spring and winter months.

Surface Water

Watershed hydrology is predominately snowmelt driven and there are three operational USGS gaging stations in the study area. These include: (1) USGS 06016000 Big Hole River below Mudd Creek, (2) USGS 06017000 Big Hole River nr Melrose, and (3) USGS 06018500 Big Hole River nr Glen. Additionally, a fourth gage exists upstream of the project site, USGS 06024450 Big Hole River below Big Lake Creek at Wisdom, MT. Mean monthly streamflow for the period of record for the four sites (1997-2006) is shown in fig. 2b. Typically, spring snowmelt begins in mid to late March, peaks in June, and then rapidly declines in July and August toward baseflow. Minimum discharges usually occur during late summer months and often result in late-season shortages of irrigation water (Marvin and Voller, 2000). Tributary inflow to the Big Hole River is highly variable, and depends largely on drainage area and basin elevation. The largest tributary to the Big Hole River is Wise River, which contributes mean annual discharge of 3.9 cms (138 cfs). Other important tributaries in the study reach include Fishtrap Creek, LaMarche Creek, Deep Creek, Divide Creek, and Willow Creek..

Groundwater

According to Marvin and Voeller (2000), tertiary and quaternary sediment deposits are the most important hydrogeologic features of the Big Hole River. These stratigraphic layers form the extensive groundwater system that immediately underlies the Big Hole River. Both Marvin et al., (1997) and Marvin and Voeller (2000) provide detailed information on groundwater resources in the basin. From review of their work, seasonal groundwater head fluctuations occur in excess of 1.5-4.5 m (5-15 feet) during the irrigation season as a result of percolation losses from irrigated pastures and irrigation canals. Losses, combined with spring rain and snowmelt, contribute to substantial gains in aquifer storage during May and June. In late summer (e.g. July and August), infiltrating water is thought to be consumed by evapotranspiration (ET) rather than being returned to surface water. Finally, at the onset of plant dormancy, return flow again becomes a significant component of the water balance and streamflow gains of 2.5 cms (90 cfs) are reported. During the period of 1997-2006, a gain of 3.25 cms (115 cfs) was observed (fig. 2b).

Groundwater-Surface water

Several groundwater-surface water interaction studies have been completed in the Big Hole Watershed in recent years. Levings (1986) noted that flood irrigation in the upper watershed was a significant contributor of recharge to the near surface aquifer. Marvin (1997) quantified the extent of surface water losses and found that 0.027 cms per km (0.6 cfs per mile) was lost from irrigation ditches to groundwater. Further work completed by Marvin and Voller (2000) confirmed that irrigation losses in the basin were significant. They documented gains in groundwater storage and associated return flows during the spring and fall months. In the summer, much of this water is consumed by ET rather than being discharged back to the river through return flow and/or shallow groundwater accretion.

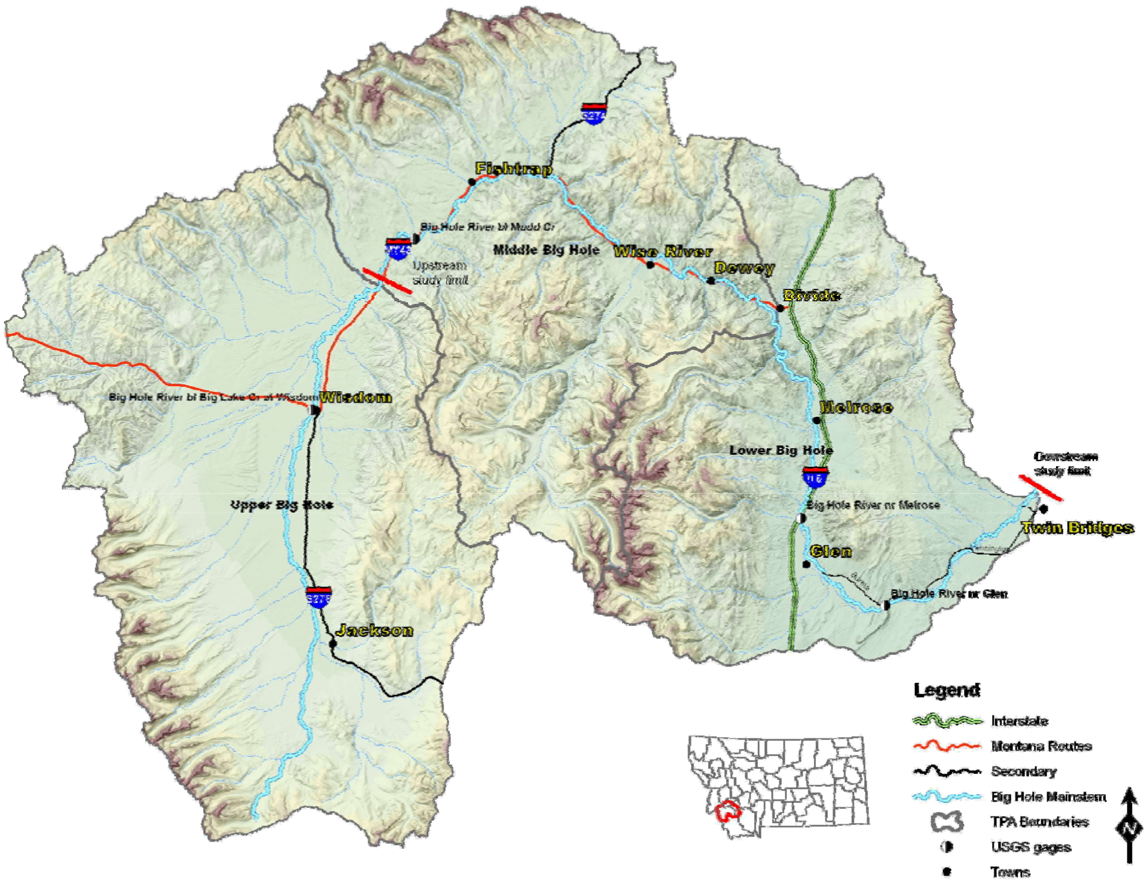
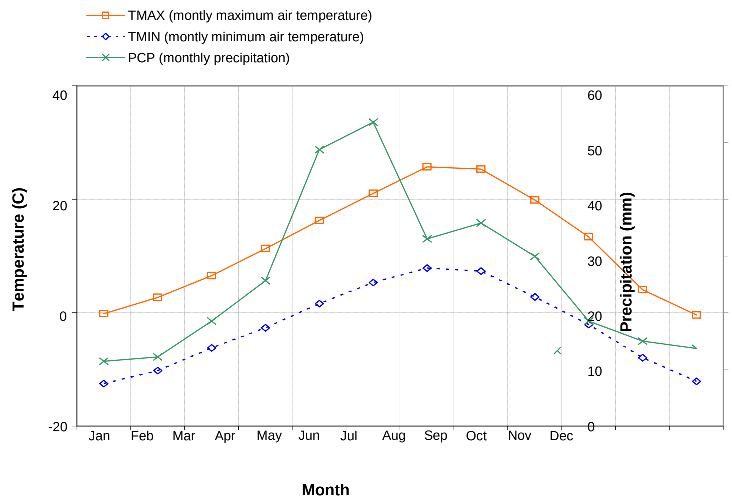
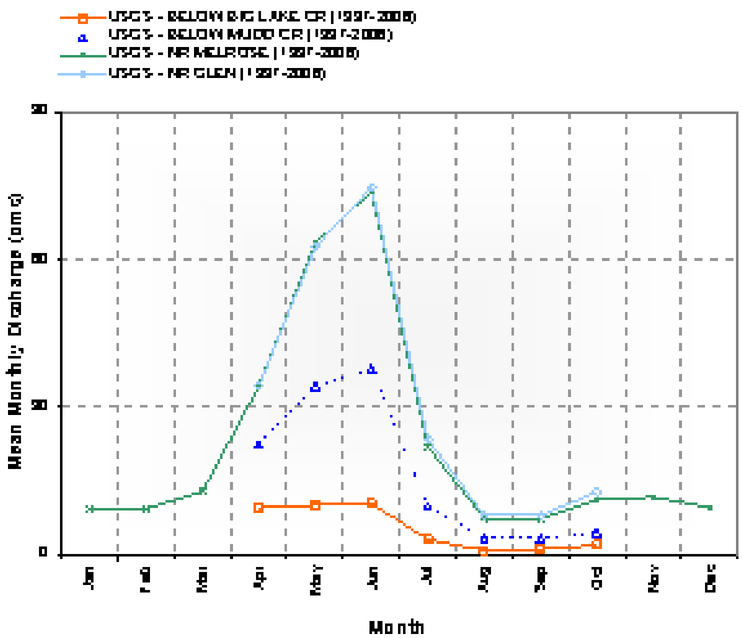


Figure D-1. Big Hole River watershed, hydrography, and stream-flow gaging stations. The modeling reach extends from downstream of Wisdom to the watershed outlet near Twin Bridges, MT. The limits of the project reach are delineated in red.



a)



b)

Figure D-2. Big Hole River climate at Divide 2 NW (1971-2000); b) USGS hydrology.

Irrigation & Domestic Use

Alfalfa and grass hay production are the primary agricultural practices in the Big Hole River watershed that require irrigation. Two cuttings of hay occur in the lower basin while the upper basin is limited to one due to climate. Irrigation water is typically distributed through unlined ditches and canals, with field application by either flooding or sprinkler (Marvin and Voller, 2000). Irrigation is reported heaviest downstream of Melrose. According to Wells and Decker-Hess (1981), withdrawals in the lower Big Hole between Melrose and Twin Bridges have ranged from between 2.27 to 5.95 cms (80-210 cfs), with up to 9.29 cms (328 cfs) being removed from the river during the summer of 1980. Bahls (1978) qualitatively supports this assertion reporting 44 diversions between Divide Creek and the mouth. While irrigation in the upper Big Hole is less documented, it is still significant. In 2004 a total of 15 ranchers were paid to stop irrigating approximately 5,500 ha (13,685 acres) in the upper basin with financial assistance from the Natural Resources Conservation Service (NRCS). Prior to implementation, the river was dewatered to 0.85 cms (30 cfs). Days after shutoff streamflow rose significantly (MRA, 2007). Note: DEQ's review of this event indicates the response was likely biased from rains and associated runoff response.

Domestic water use in the Big Hole is somewhat limited. The primary user is the Butte-Silver Bow Water Utility. During July 2006, average pumping from the Feeley Plant near Divide was 0.38 cms (13.4 cfs).

METHODS AND MATERIALS

An intensive field data collection effort was completed during the summer of 2006 to characterize continuous water temperature, meteorological forcings (e.g. air temperature, relative humidity, wind speed, etc.), and the associated water balance in support of the modeling effort. The intensive one-week synoptic monitoring program was supplemented with information from the USGS National Water Information Program, National Oceanic and Atmospheric Administration (NOAA) Cooperative Observer program (COOP), Remote Automated Weather Station (RAWS) program, and Bureau of Reclamation AGRIMET network to provide comprehensive data regarding the project reach.

Site Selection

Sites for discharge and temperature monitoring were identified by DEQ as part of the original project scoping (DEQ/Watershed Consulting, 2006). In total, 20 main-stem locations, 44 tributaries and irrigation return flows, and 33 irrigation withdrawals were monitored in the field. Sites were accessed primarily by watercraft, as project teams floated through the study reach to characterize water exchanges and associated temperatures for modeling. Irrigation diversions were identified using Montana Water Resource Surveys (WRS) for Deer Lodge (1955), Madison (1965), and Silver Bow Counties (1955). Since no survey was published for Beaverhead County, these points were identified in the field by GPS, and then were later correlated with information from the Lower Big Hole River Irrigation Study currently in progress by PBS&J (J. Dunn, personal communication, February 2008).

Temperature Data

Continuous temperature data loggers were used to record diurnal variations in temperature as outlined in Barthalow (1989). Temperature dataloggers used in the Big Hole River modeling study were Optic StowAway® model number WTA32-05+37. The StowAway® is a completely sealed underwater temperature logger with capability to record continuous readings from 0.5 seconds to 9 hours. Temperature measurements were made at 15-minute increments, and were read on the hour for model input/calibration purposes. Logger calibration checks were completed both pre- and post deployment, and were within the acceptable range specified by DEQ (2007). Loggers have a NIST traceable temperature accuracy of ±0.2°C, therefore the absolute accuracy is 0.4ºC. Loggers were in the field for approximately one month.

Discharge Data

All major inflows and outflows were monitored over a one-week period to describe hydrologic flux in the watershed. Flow measurements were made using the current meter procedures discussed by Rantz (1982), or were estimated via the floating object procedure described by DEQ (1995). A combination of portable meters including a Marsh-McBirney Model 2000 Flo-Mate solid state meter, Price AA traditional meter, pygmy meter, and a propeller-based Swoffer meter were used. Relative precision of the measurements were addressed through meter tests at multiple depths within a single cross-section. Velocity variation was ±7.5 percent which is consistent with that of Harmel et al. (2000). Quality assurance (QA) checks also were made at discharge cross-section transects within ±5 percent.

Climate Data

Climate was field monitored so that measurements in the river corridor could be correlated with that of surrounding COOP, RAWS, and AGRIMET stations. Air temperature and wet bulb depression were measured with a U.S. Weather Bureau type sling phsychrometer having accuracy of ±0.5 °C. Wind speed was measured with a Dwyer hand-held wind meter (±0.2 m/s for low scales and ±1.3 m/s for high scales). Observations of cloud cover were also made to the nearest 10-percent. All measurements were completed four times daily.

Morphological and Shade Data

River morphology and riparian vegetation data were assessed in the field to characterize direct solar radiation losses from topography and vegetative shade. The following measurements were made to support the modeling: (1) bankfull and wetted channel width, (2) tree heights, (3) canopy density, (4) channel overhang, and (5) shade at specified transects. A fiberglass-tape, range-finder, clinometer, canopy densitometer, and solar pathfinder™ were used to acquire these attributes.

MODEL DEVELOPMENT

Model Description

Heatsource v7.0 is a dynamic continuous temperature model that operates on a sub hourly time-step (Boyd and Kasper, 2004). All components of the heat balance are simulated including incoming shortwave radiation, terrestrial longwave radiation, thermal conduction and convection, evaporative flux, and ground flux. Forcing functions required to simulate the heat flux across the air-water interface include air temperature, wind speed, relative humidity, and cloud cover. These interact with shade, river morphology, and adjacent tributaries to provide a comprehensive description of mass/heat transfer and advection/dispersion throughout the simulated system. Springs, tributaries, and return flows are assumed to be mixed instantaneously over the finite difference step in the model, and trapezoidal channel geometry and Manning's equation are used to estimate flow velocity and associated hydraulics for a given discharge and reach configuration. Evaporation is simulated using either a simplified mass transfer function, or a version the Penman method (Dingman, 2002). Dynamic water routing is completed by simultaneous solution of the St. Venant equations for continuity and momentum using either the Muskingum approximation or explicit finite difference method. Hyporheic flow is also simulated.

GIS Pre-processing

Heatsource v7.0 includes a spatially explicit ArcView3.2 GIS pre-processor called TTools for efficient calculation of morphologic and shading attributes at river scales (Boyd and Kaspar, 2004). Fundamental input data required for implementation of TTools includes: (1) site topography in the form of a digital elevation model (DEM), (2) digitized channel morphology (e.g. bankfull widths and centerline), (3) digitized riparian vegetation shapefile, and (4) user-defined vegetation characteristics. The 30-m USGS National Elevation Dataset (NED) was used for calculation of topographic characteristics. Channel centerline, bankfull geometry, and riparian vegetation classification were all digitized by DEQ using 2004 National Agricultural Imagery Program (NAIP) photography at a scale of 1:5,000. These were then converted to 1-m grid resolution for model pre-processing. Project coordinate system and datum were State-Plane NAD83 and NAVD88.

TTools includes a longitudinal and radial sampling algorithm that calculates site-specific morphologic and shading characteristics such as channel width and slope, topographic shade, and vegetative shade at user defined nodes (i and i+1) along the channel centerline (**fig. D-3**). A node distance of 100-m was used in the case of the Big Hole River and radial samples were completed at 15-m spacing to determine landcover attributes (e.g. tree height, density, channel overhang, etc.) for associated shading calculations. Additional information on TTools and Heatsource v7.0 setup are discussed in subsequent sections.

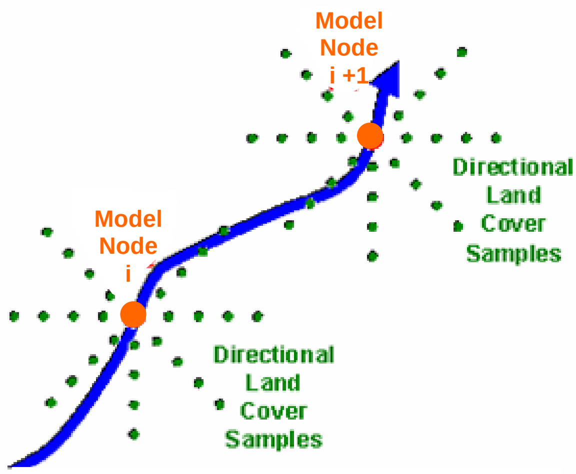


Figure D-3. Example of TTools radial sampling algorithm.

Simulation Period and Global Control Specifications

Following the initial pre-processing, the model simulation period was chosen to be consistent with the critical limiting period, i.e. where standards are most likely to be exceeded. Based on a review of water temperature data at USGS 06025500 Big Hole River nr Melrose MT (2000-2006) (**fig. D-4**), this period most frequently occurs in late July to early August, when air temperatures are the highest, and when photoperiod is sufficiently long. Thus the field data-collection was pre-scheduled to be coincident with this time period. Ultimately, the week of July 25-31, 2005 was used in the modeling. Other information specified during initial project planning were control information such as finite difference distances (dx) and time steps (dt)], evaporation approaches, and routing methodologies. Several combinations of dx/dt were evaluated as part of initial model testing including 500, 1,000, and 2,000-m distances and 5, 10, and 15 minute time increments. The combination of a 10-minute time-step and 1,000-m distance step was found to most readily balance model run time with computational rigor. The mass transfer evaporation approach (using Penman coefficients) and Muskingum channel routing were used as available data did not support use of more complex methodologies.

Hydrology/Mass Transfer Input

Hydrology and mass transfer data from the 2006 field effort were used to define the overall water balance and associated boundary conditions for the modeling (**table D-1**). Prior to the initiation of the project, flow conditions were evaluated in context with the historical gage record to determine their relative relationship with know low flow-frequency. As observed in **fig. D-4**, mean daily discharge at the USGS gage near Melrose for July 25-31, 2006 was approximately 4.2 cms (150 cfs). The mean daily statistic is nearer 17 cms (~600 cfs). This indicates that flows during 2006 were roughly equivalent to the 7-day, 5-year low flow condition (7Q5) (McCarthy, 2004); a duration and frequency that DEQ feels is appropriate for temperature study. Thus the model application was developed for the 7-day period of July 25-31, 2006; at, or near, the 7Q5. Locations of all hydrology/mass transfer monitoring sites are shown in **fig. D-5**. A more detailed map is in **Appendix-A**.

As seen in **fig. D-6a** and **b**, the hydrograph during the modeling period is clearly characteristic of unsteady flow conditions. Analysis of the 7-day period from July 25-31, 2006 indicates that a headwater change of nearly 50 percent occurred at the upstream end of the project reach (USGS gage near Wisdom). Subsequent downstream gages also exhibit similar effects. Given such large variation over a relative short time-period, it was decided that a dynamic upstream boundary condition was necessary to adequately reflect in-river flow conditions. Hourly data from the USGS Mudd Creek gage were used to distribute flow through time at this site. All other hydrology/mass transfer boundaries were considered steady-state, an assumption that was largely necessitated due to the fact that continuous flow monitoring of tributaries/irrigation exchanges was not feasible. Identified cross-correlation between USGS gages in the upper and lower reaches, further supports the steady-flow assumption.

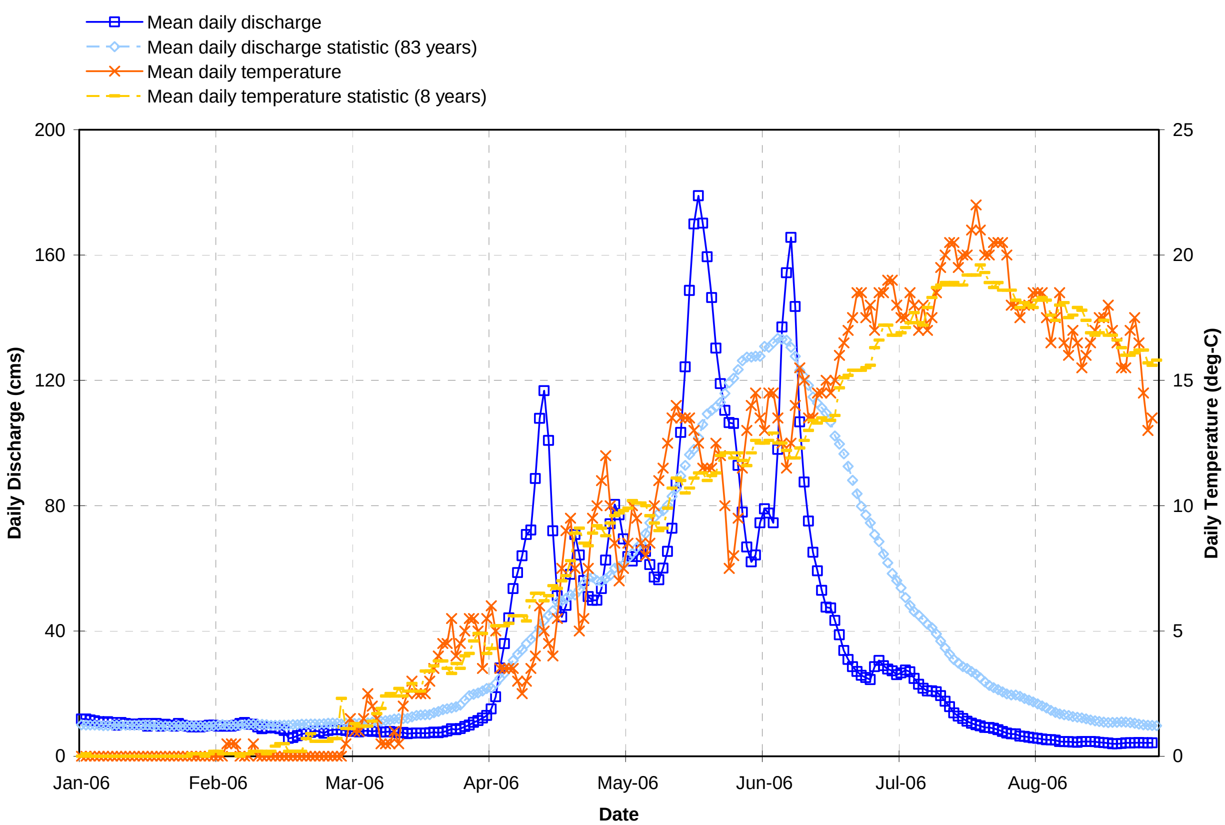


Figure D-4. Summary of mean daily discharge, temperature, and associated statistics for the USGS gage near Melrose, MT (USGS 06025500). Data from USGS National Water Information System (NWIS).

Table D-1. Instantaneous measured inflow, outflow, and associated water balance for the Big Hole River during the July 25-31, 2006 modeling period. All data are in cubic meters per second (m^3/s).

BIG HOLE RIVER WATER BALANCE 7/25-31/06	m^3/s	GWH_2O EST
Z01 - BIG HOLE RVR BELOW PINTLAR CR	**2.917**	
R02 - C-S WASTE RT	0.010	
R48 - BACON-NYHART RT	0.057	
R61 - SEEFIELD RT	0.028	0.064
R03 - MUDD CR	0.021	
R04 - SQAW CR	0.046	
TOTAL	**3.079**	**GAINING**
USGS 06016000 - BIG HOLE RVR @ MUDD CR	**3.143**	**3.143**
R52 - TOOMEY SPRING	0.012	
R54 - TOOMEY CR	0.014	0.824
TOTAL	**3.169**	**GAINING**
Z02 - BIG HOLE RVR 4.5 KM BELOW MUDD CR	**3.993**	**3.993**
T05 - SAWLOG CR	0.038	
R58 - STEWART CR	0.187	
R60 - PADDOCK/SOPER RT	0.020	0.080
R06 - FISHTRAP CR	0.779	
TOTAL	**5.017**	**GAINING**
Z03 - BIG HOLE RVR BELOW FISHTRAP FAS	**5.097**	**5.097**
R07 - LAMARCHE CR	0.575	0.077
TOTAL	**5.672**	**GAINING**
Z04 - BIG HOLE RVR BELOW SEYMOUR CR	**5.749**	**5.749**
R09 - BACON RTN	0.028	
R01 - SEYMOUR CR	0.116	
R05 - DEEP CR	0.767	-0.605
R08 - BRYANT CR	0.125	
A06 - BEAR CR	0.050	
TOTAL	**6.835**	**LOSING**
Z06 - BIG HOLE RVR ABOVE JOHNSON CR	**6.230**	**6.230**
R26 - JOHNSON CR	0.075	
A11 - ALDER CR	0.040	
R40 - UNNAMED DVT	-0.133	
R29 - MEADOW CR	0.170	-1.087
R31 - MEADOW CR RT	0.130	
TOTAL	**6.512**	**LOSING**
Z22 - BIG HOLE RVR ABOVE WISE RIVER	**5.425**	**5.425**
R71 - WISE RVR-1 (WEST)	1.463	
R32 - WISE RVR-2 (EAST)	0.595	0.076
TOTAL	**7.483**	**GAINING**
Z07 - BIG HOLE RVR ABOVE JERRY CR	**7.559**	**7.559**
R33 - JERRY CR	0.073	
I10 - SRING GULCH	0.087	2.897
TOTAL	**7.719**	**GAINING**
Z46 - BIG HOLE RVR NR POWERHOUSE FAS	**10.616**	**10.616**
O01 - BH PUMP ST. DVT	-0.439	
O08 - DIVIDE CANAL DVT	-0.700	
I11 - SHELTON-KAMBICH DVT	-0.255	
R39 - SHELTON-KAMBICH RT	0.023	-0.712
R10 - UNNAMED DVT	-0.084	
R38 - SHELTON-KAMBICH RT	0.028	
TOTAL	**9.189**	**LOSING**
Z21 - BIG HOLE RVR ABOVE DIVIDE CR	**8.477**	**8.477**
R16 - DIVIDE CR-1 (EAST)	0.102	
R20 - DIVIDE CR-2 (WEST)	0.085	1.052
I16 - UNNAMED TRIB (GOAT MTN)	0.079	
TOTAL	**8.743**	**GAINING**
Z08 - BIG HOLE RVR @ MAIDENROCK CANYON	**9.795**	**9.795**
R35 - CANYON CR	0.112	
I50 - MOOSE CR	0.238	
I17 - MCCAULY-1 DVT	-0.586	0.578
R12 - MERIWETHER DVT	-0.470	
TOTAL	**9.089**	**GAINING**
Z09 - BIG HOLE RVR NR MAIDENROCK FAS	**9.667**	**9.667**
Z09 - BIG HOLE RVR NR MAIDENROCK FAS	**9.667**	**9.667**
R34 - MCCAULY-2, MELROSE DVT	-0.484	
R15 - MERIWETHER RTN	0.189	
R36 - SOAP CR	0.064	
I20 - ROBBINS (MERIWETHER) DVT	-0.057	
O02 - BOWE (CARPENTER) DVT	-0.163	
R23 - CAMP CR	0.021	1.563
O03 - STREB (PENDERGAST) DVT	-0.156	
O07 - GALLAGHER DVT	-0.445	
I27 - TRAPPER CR	0.068	
TOTAL	**8.704**	**GAINING**
Z10+11 - BIG HOLE RVR NR SALMON FLY FAS	**10.267**	**10.267**
I24 - CHERRY CR	0.092	
R18 - GALLAGHER-STREB RT	0.295	
I40 - KALSTA DVT	-0.334	
O23 - HAGENBARTH-1 DVT	-0.585	-1.135
R37 - ROCK CREEK	0.041	
O22 - HAGENBARTH-2 DVT	-0.174	
TOTAL	**9.602**	**LOSING**
Z12 USGS 06017000 - BH RVR NR MELROSE	**8.467**	**8.467**
I31 - KALSTA RT	0.239	
O20 - GAINY DVT	-0.070	-1.667
EST - GARRISON-KILWIEN DVT	-0.500	
TOTAL	**8.136**	**LOSING**
Z13 - BIG HOLE RVR NR GLEN FAS	**6.469**	**6.469**
R27 - WILLOW CR	0.450	
O10 - STEVENS SLOUGH (GARRISON) DVT	-0.113	
R28 - BIRCH CR	0.025	
O11 - COCANOUGHAR-1 (RAFFERTY) DVT	-0.175	1.886
O12 - COCANOUGHAR-2 (RAFFERTY) DVT	-0.238	
O13 - BRYAN DVT	-0.120	
TOTAL	**6.298**	**GAINING**
Z14 - USGS 06018500 - BH RVR @ NOTCH FAS	**8.184**	**8.184**
O05 - LARSON-NARANICH (JS) DVT	-0.750	-0.864
TOTAL	**7.434**	**LOSING**
Z15 - BIG HOLE RVR ABOVE PAIGEVILLE DVT	**6.570**	**6.570**
R30 - LARSON-NARANCICH RT	0.207	
O14 - SANDY DITCH DVT	-0.133	
O15 - PAIGEVILLE CANAL	-1.642	0.693
I37 - NARANCICH DVT	-0.600	
I38 - SANDY DITCH RT	0.200	
TOTAL	**4.602**	**GAINING**
Z16 - BIG HOLE RVR @ PENNINGTON BR FAS	**5.295**	5.295
I90 - PENNINGTON BR DVT	-0.060	
O17 - OWSLEY SLOUGH (BH COOP)	-2.197	0.345
I41 - PENNINGTON BR RT	0.015	
TOTAL	**3.053**	**GAINING**
Z17 - BIG HOLE RVR ABOVE THIRD SLOUGH	**3.398**	3.398
O18 - THIRD SLOUGH (ORPHAN HOME)	-0.269	
O19 - LOGAN-SMITH DVT	-0.174	-0.059
O21 - LOTT-HARVEY DVT	-0.271	
TOTAL	**2.684**	**LOSING**
Z18+Z19 - BIG HOLE RVR NR HIGH ROAD FAS	**2.625**	2.625
O68 - SIEDENSTICKER (HAMILTON) DVT	-0.049	
O67 - UNNAMED DVT	-0.150	
TOTAL	**2.426**	**LOSING**
CONFLUENCE W/ BEAVERHEAD	NO MEASUREMENT	**END**
Z20 - BEAVERHEAD RVR		4.531
COMBINE - JEFFERSON RVR HEADWATERS		6.957

Notes:

(1) Z01, R02, R48, etc. – field measurement ID (not necessarily in alphanumeric order)

(2) Those field measurement ID's with "A" or "I" prefix estimated in field using floating object method

(3) Z05 (Dickie Bridge) – flow measurement did not meet QA/QC requirements

(4) DVT = diversion

(5) RT = return flow

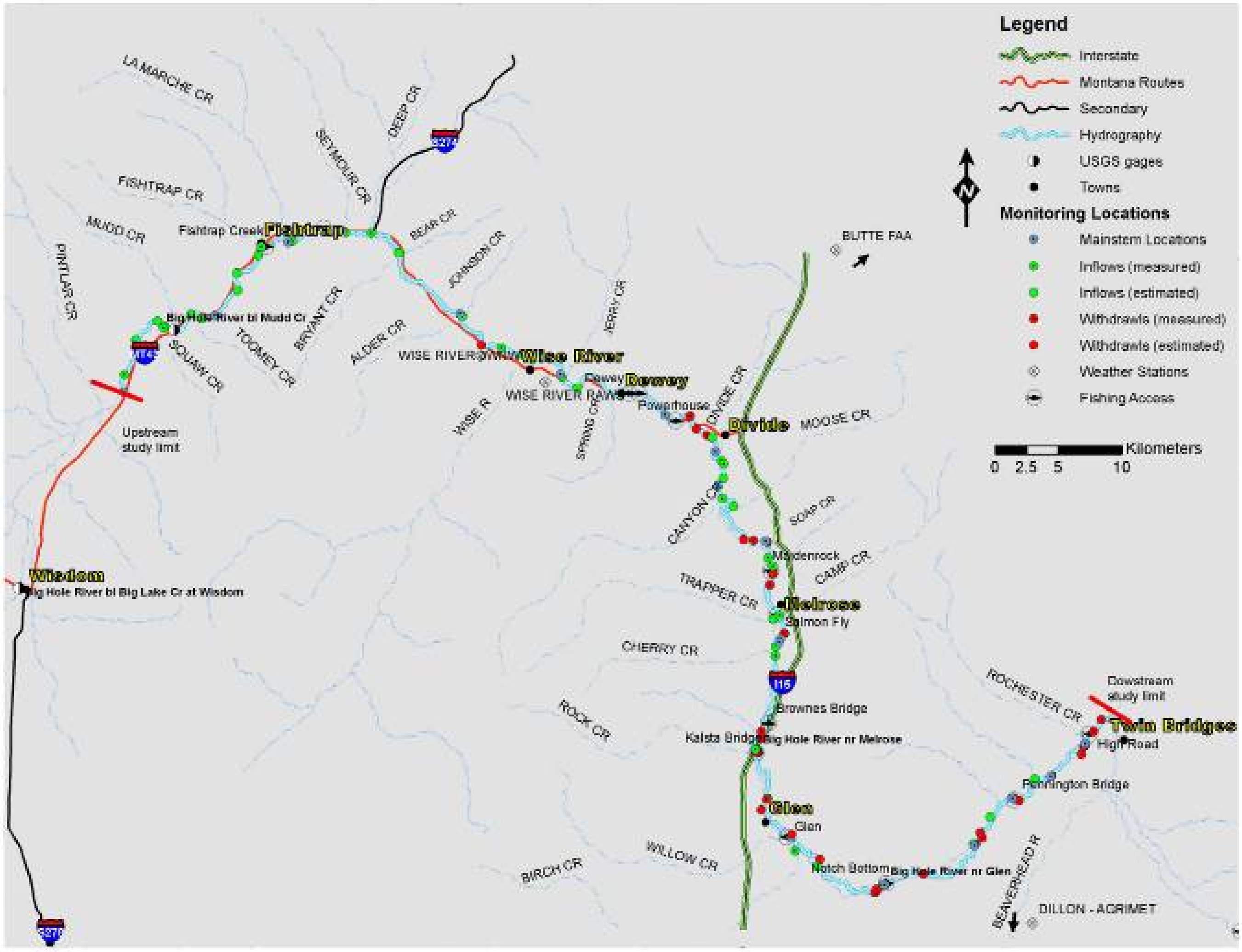


Figure D-5. Locations of major inflow, outflow, and climate monitoring on the Big Hole River.

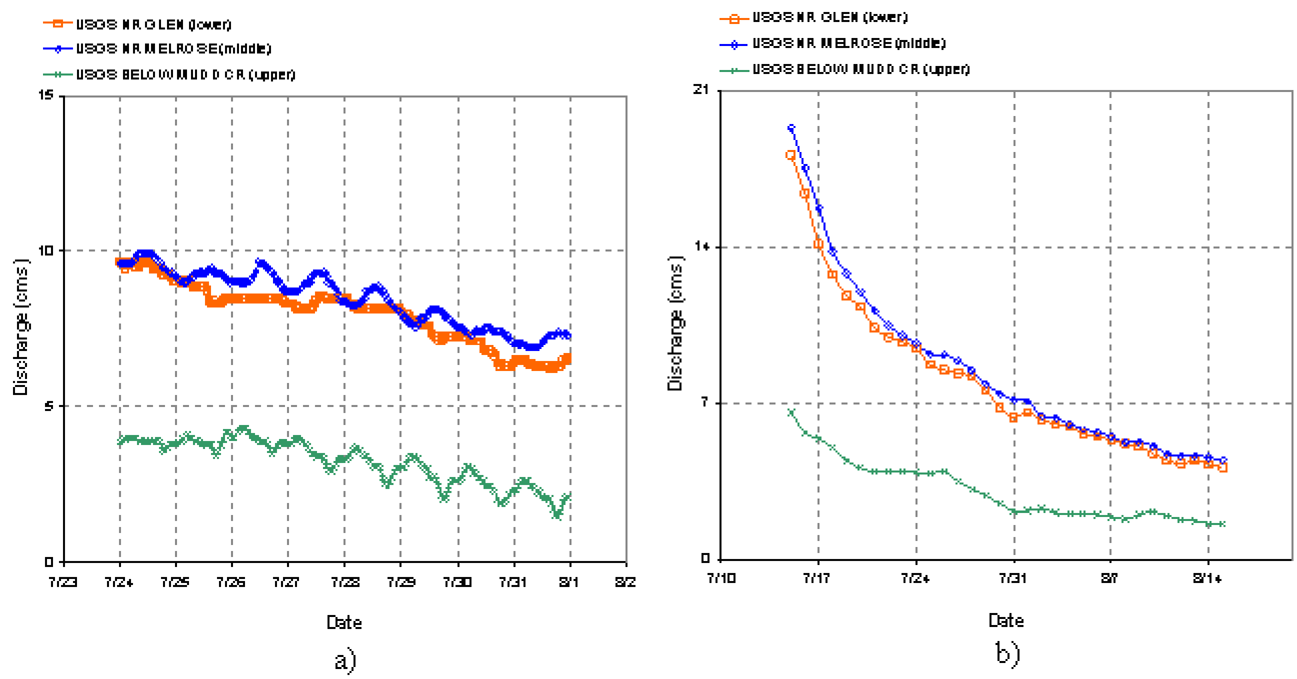
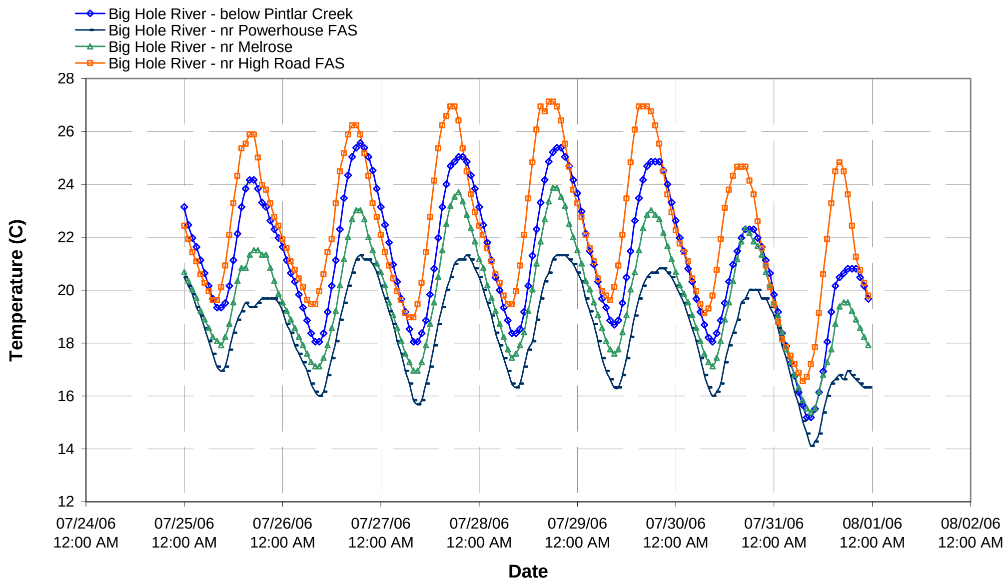


Figure D-6. Streamflow during the critical temperature limiting period a) streamflow during the critical temperature limiting period - 2006; b) hourly plot Jul. 25-31; daily plot Jul. 15-Aug. 15.

While discharge measurements were input as steady-flow (with the exception of the headwater condition), temperature measurements were made as time-variable using data from Hobo temperature loggers. In locations where continuous temperature data were not collected, instantaneous field measurements were completed such that an hourly distribution could be developed from the relationship between instrumented and un-instrumented sites. Aspect, proximity, and contributing watershed area were the primary attributes used in the paired watershed approach. Given the voluminous amount of data collected at these sites, much of it cannot be presented in the text of this report. However, a subset of hourly plots for both mainstem and tributary sites are shown in **fig D-7a** and **D-7b**. In general, tributaries exhibit greater diel fluctuation than mainstem sites. They are also much cooler. In both locations, temperatures reach maximums at approximately 6:00-7:00 p.m., while nighttime minimums occur in the morning at 9:00 to 10:00 a.m.

Box and whisker plots from incoming tributaries to the Big Hole River are shown in **fig. D-8**. While minimums and maximums vary throughout the watershed, it is recognized that irrigation return flows often have a much larger range of maximum and minimum temperatures, and associated quartiles, compared to that of natural tributary flow. This is most likely a function of flow volume at these sites and forms a preliminary understanding of the cumulative influence of irrigation returns on water temperature.

a)



b)

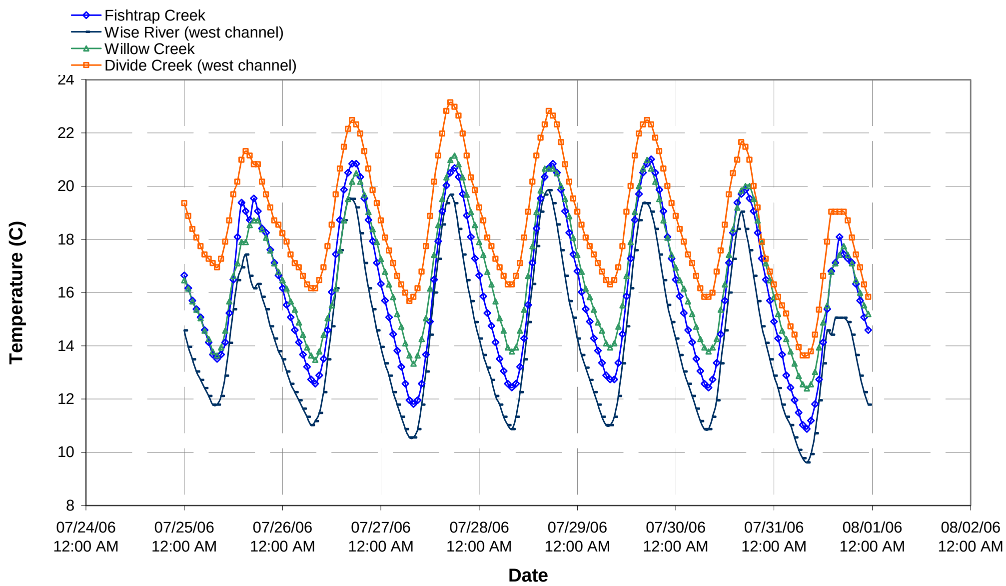


Figure D-7. Hourly plots of water temperature for selected a) mainstem and b) tributary monitoring stations on the Big Hole River for the July 25-31, 2006 monitoring period.

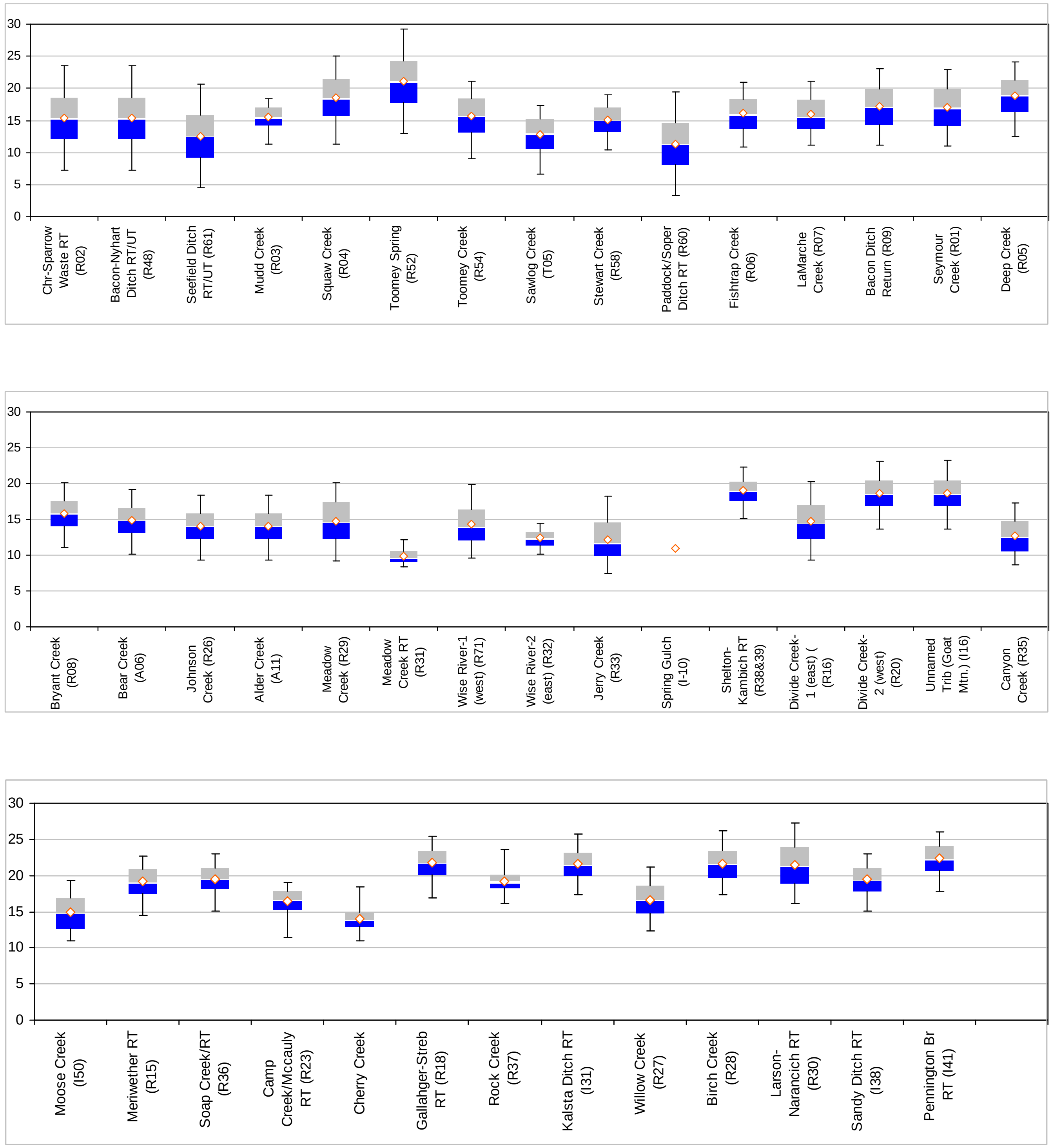


Figure D-8. Box and whisker plots of tributary temperature data collected on the Big Hole River from the July 25-31, 2007. From top left to bottom right, plots are in sequential order going downstream.

Hydraulic Input

Bankfull width, width-depth ratio, channel side slope, gradient, Muskingum routing coefficients, and Manning's roughness coefficients are all required hydraulic inputs for Heatsource v7.0. Unknown variables such as velocity, depth, and wetted channel width are then computed for a given flow condition using Manning's equation and assumed trapezoidal channel geometry. Hydraulic input for the model was developed as follows: (1) bankfull width was measured in the GIS at 100-m intervals using digitized left and right bank polylines as part of the initial TTools processing, (2) width-depth ratio and channel side slope were regressed using measured field parameters, and (3) Manning's roughness coefficient was directly estimated from USGS gage sites using known channel geometry and a wide channel approximation. Roughness values were shown to much higher than those typically published in the literature (0.05-0.14; see Chow 1959; Sturm, 2001). This is reflective of the increasing effect of resistance with decreasing hydraulic depth, filamentous algae, pools and riffles, and other unknown obstructions USACE (1993). Values of 0.09-0.12 were used in the modeling (see **Appendix-A**). Fourteen reaches were identified for unique parameterization of hydraulics based on channel gradient from the USGS NED (**fig. D-9**). They were characterized as shown in **table D-2**.

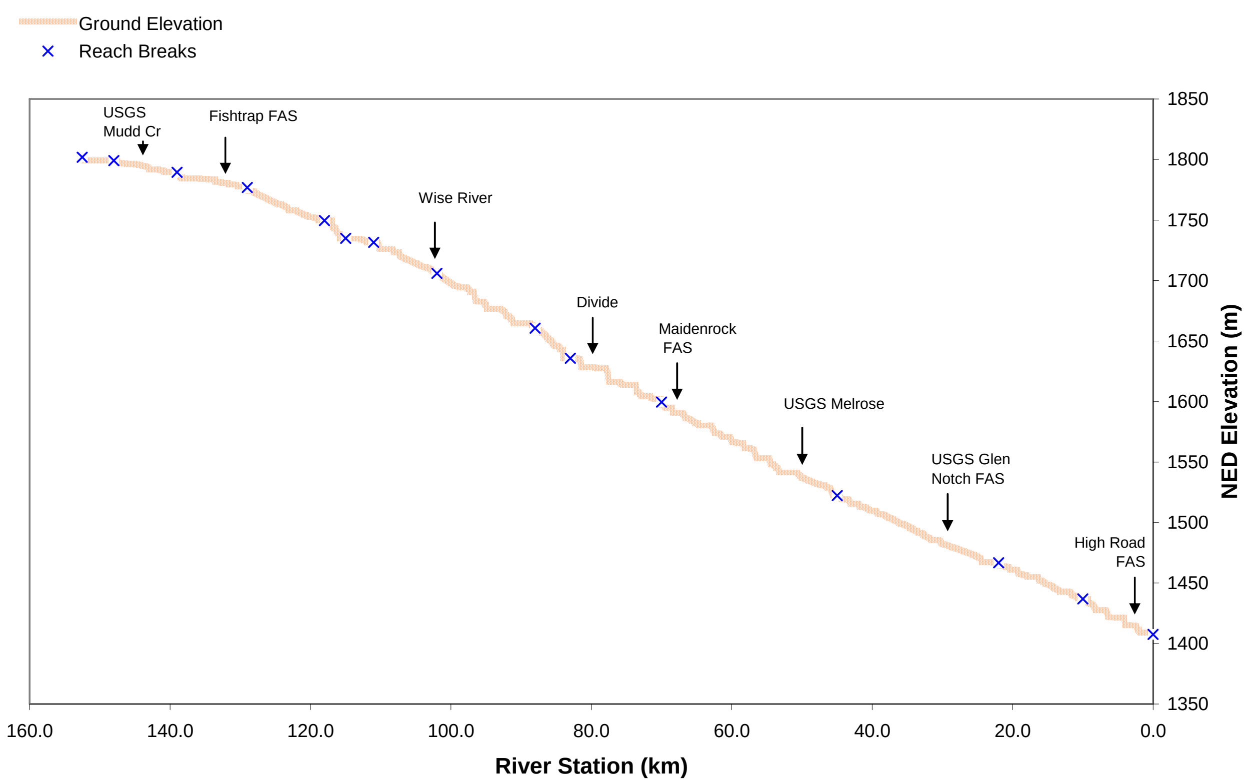


Figure D-9. Unique reaches defined for model parameterization of hydraulics. Elevation data taken from USGS National Elevation Dataset (NED) 30-m grid.

Climate Input

Three climate stations were used to provide hourly temperature (°C), wind speed (m/s), and relative humidity (%) data for the modeling effort. The Wise River RAWS site, Bert-Mooney FAA (e.g. Butte), and Dillon Valley Agrimet station were apportioned to representative modeling reaches to account for localized climate. Because meteorological data collected outside of the river corridor is at times not representative of conditions encountered near the river (Troxler and Thackston, 1975; Bartholow 1989), field measurements taken from within the river corridor were used to perform a climate adjustment. Of all inputs adjusted (e.g. temperature, wind speed, and relative humidity), relative humidity was found to vary the most between locations. At times, it was 15-20 percent greater in the river corridor than at surrounding climate stations. Climate data used in the modeling are shown in **fig. D-10**.

Shade Input

Fifteen riparian landcover types were identified through air photo interpretation and ground-truth to parameterize typical reach shading attributes in the model (**table D-3**). Verified model parameters were then assigned to corresponding land classes to form the base input for radial shading calculations in Heatsource v7.0. An example of the digitized landcover used for this process is shown in **fig. D-11** (near Melrose and the Salmon Fly FAS).

Table D-2. Hydraulic parameters used in the Big Hole River Heatsource v7.0 model.

River Reaches	Gradient (%)	Width- Depth Ratio	Mannings "n"
Reach 1	0.062%	90	0.09
Reach 2	0.108%	80	0.09
Reach 3	0.126%	80	0.09
Reach 4	0.249%	80	0.10
Reach 5	0.490%	70	0.10
Reach 6	0.082%	70	0.10
Reach 7	0.284%	70	0.10
Reach 8	0.324%	70	0.10
Reach 9	0.496%	70	0.10
Reach 10	0.302%	70	0.10
Reach 11	0.297%	60	0.10
Reach 12	0.242%	60	0.10
Reach 13	0.248%	50	0.12
Reach 14	0.293%	50	0.12

Table D-3. Riparian landcover types and associated attributes used in Heatsource v7.0 shading calculations.

Land Cover	Height (m)	Density (%)	Over-hang (m)
Bare	4.9	40%	0.00
Coniferous (sparse)	5.7	75%	0.10
Coniferous (dense)	17.2	40%	0.10
Deciduous (sparse)	18.9	85%	0.30
Deciduous (dense)	14.5	55%	0.00
Grass/sedge (sparse)	16.0	85%	0.00
Grass/sedge (dense)	0.4	50%	0.00
Grass 75%/deciduous 25%	0.5	90%	0.10
NSDZ/water	2.9	64%	0.05
Transportation	11.7	60%	0.13
Willow (sparse)	12.9	63%	0.08
Willow/ (dense)	0.0	0%	0.00
Willow/deciduous	0.0	0%	0.00
Willow/deciduous/conifer	4.9	68%	0.09
Willow 50%/grass 50%	0.0	0%	0.00

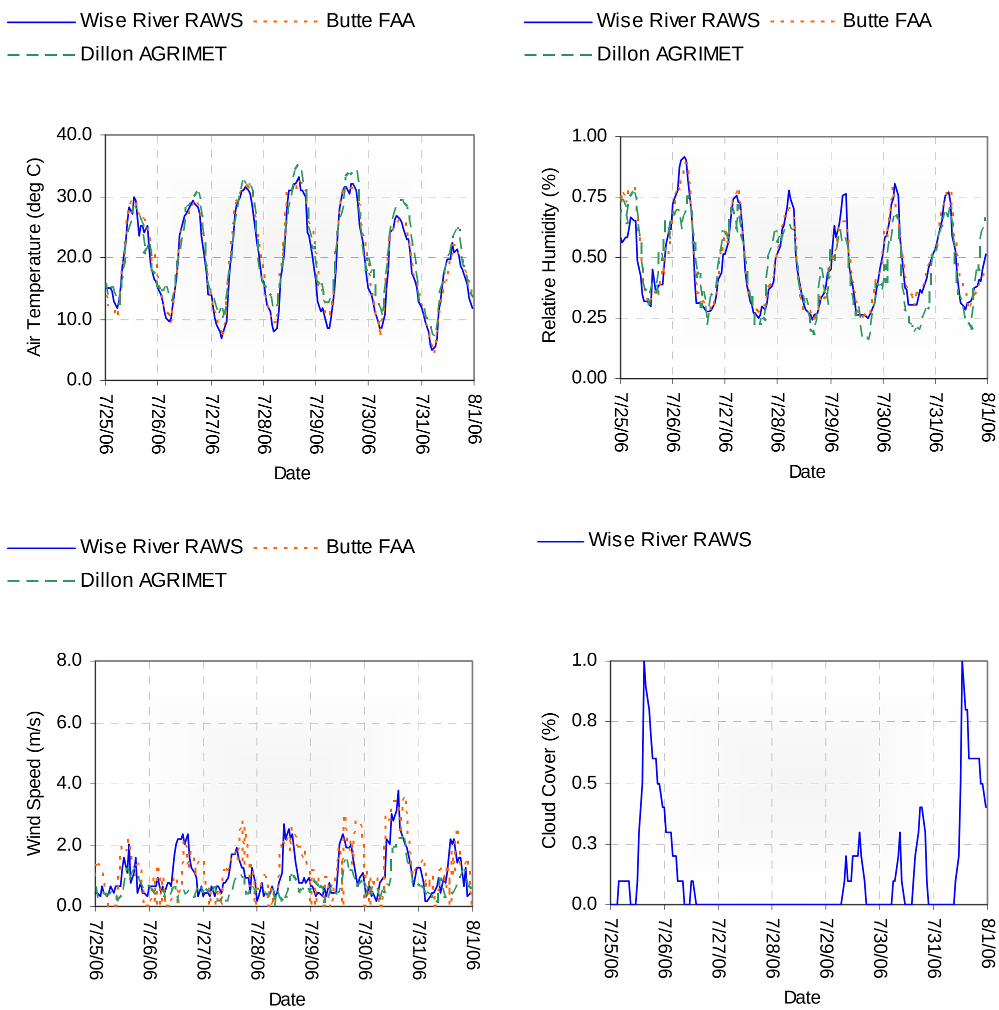


Figure D-10. Adjusted climatic conditions over the July 25-31, 2006 modeling period at the three localized climate stations.

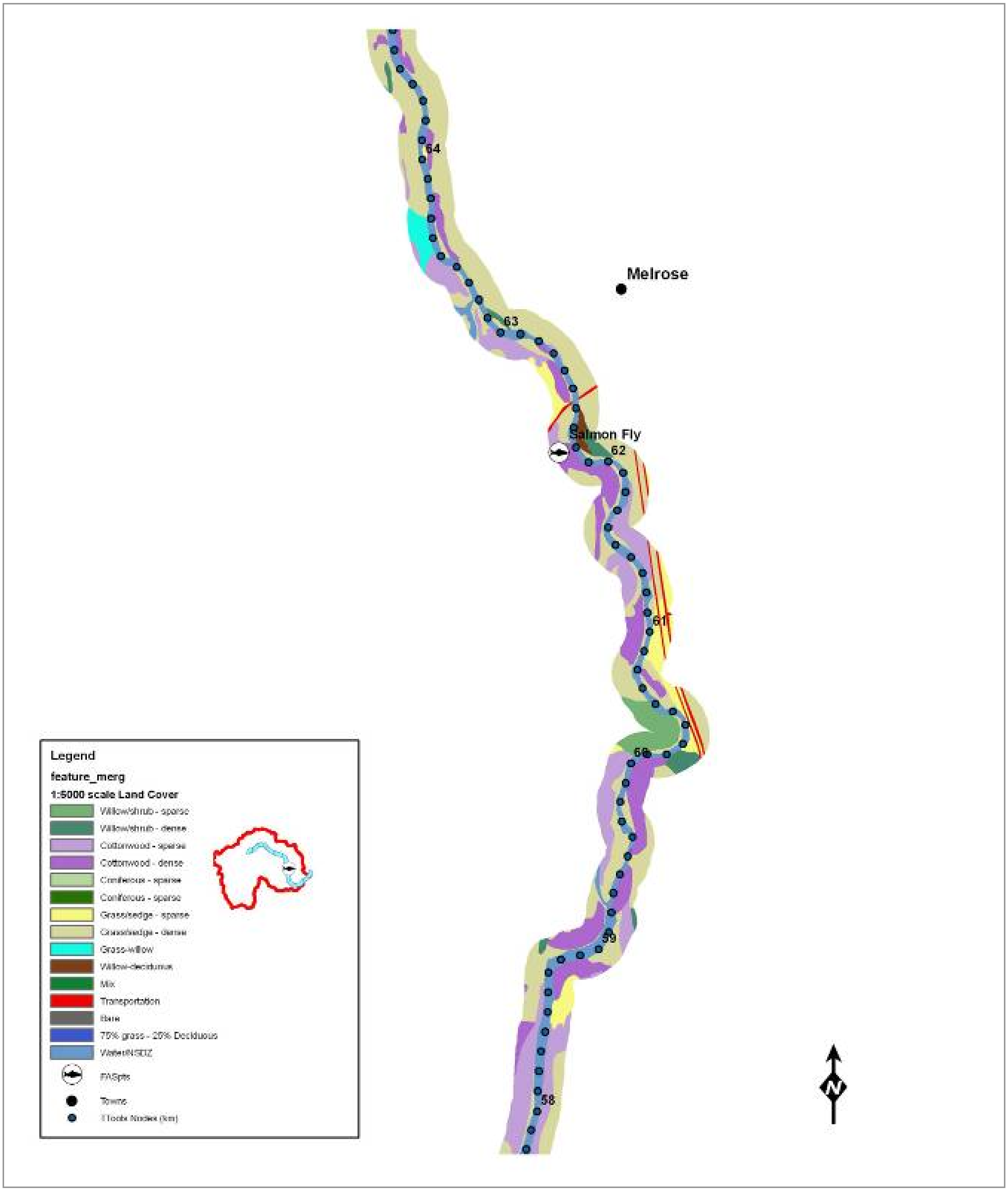


Figure D-11. Example of digitized riparian landcover classification used in the Big Hole River Model near Melrose. The 2004 NAIP imagery was used at a 1:5,000 scale to produce a 1-m raster landcover dataset.

Model Evaluation Criteria

Following model input development, performance statistics were selected to assess hourly and 7-day average temperature predictions from Heatsource v7.0. The first criterion was percent bias (PBIAS), which is a measure of the average tendency of the simulated temperatures to be larger or smaller than an observed value. Optimal PBIAS is 0.0 while a positive value indicates a model bias toward overestimation. A negative value indicates bias toward underestimation. PBIAS is calculated as follows:

$$PBIAS = \frac{\sum_{i=1}^{n}(T_{isim} - T_{iobs})}{\sum_{i=1}^{n}(T_{iobs})} \times 100 \quad (1)$$

where

PBIAS = deviation of temperature in percent
Tiobs = observed temperature (ºC)
Tisim = simulated temperature (ºC)

DEQ has defined acceptable model bias as less than or equal to ±5 percent, more stringent than typically reported in the literature [Van Liew et al. (2005) and Donigian et al. (1983)]. The second evaluation criterion used in evaluation of model efficiency was the Nash-Sutcliffe coefficient of efficiency (NSE; Nash and Sutcliffe, 1970). NSE expresses the fraction of the measured temperature variance that is reproduced by the model. As error in the model is reduced, the NSE coefficient is inherently increased. Simulation results are considered to be good for NSE > 0.75, while values between 0.75 and 0.36 are considered satisfactory (Motovilov et al. 1999). NSE is calculated as:

$$NS_E = 1 - \frac{\sum_{i=1}^{n}(T_{iobs} - T_{isim})^2}{\sum_{i=1}^{n}(T_{iobs} - T_{avg})^2} \quad (2)$$

where

NSE = coefficient of efficiency
Tavg = average simulated temperature (ºC)

A final criterion used in the Big Hole River modeling is the sum of squared residuals (SSR), which is a commonly used objective function for hydrologic model calibration. It compares the difference between the modeled and observed ordinates, and uses the squared differences as the measure of fit. Thus a difference of 2°C between the predicted and observed values is four times worse than a difference of 1°C. Squaring the differences also treats both overestimates and underestimates by the model as undesirable. The equation for calculation of SSR is shown below (Diskin and Simon, 1977).

$$SSR = \sum_{i=1}^{n}(T_{iobs} - T_{isim})^2 \quad (3)$$

where

SSR = sum of squared residuals

Sensitivity Analysis & Model Uncertainty

Model uncertainty was assessed using a simple one-at-a-time (OAT) sensitivity analysis with parameter perturbations of ±10 percent and ±30 percent. The OAT methodology ensures that changes in output can unambiguously be attributed to the changes in model input. Parameter sensitivity is typically expressed as a normalized sensitivity coefficient (NSC) as shown below (Brown and Barnwell, 1987).

$$NSC = \left| \frac{\Delta Y_o / Y_o}{\Delta X_I / X_I} \right| \qquad (4)$$

where

NSC = normalized sensitivity coefficient

ΔYo = change in the output variable Yo

ΔXi = change in the input variable Xi

NSCs for model parameters in Heatsource v7.0 are shown in **table D-4** and are taken as the average results of the four sensitivity runs for the most downstream modeling node (±10 percent and ±30 percent perturbations). Results indicate that parameters directly related to heat flux or mass transfer (ground temperature, air temperature, relative humidity, groundwater flow, and tributary flow) are highly sensitive in the Big Hole River watershed. Those related to flow routing were not (roughness, Muskingum-x, width-depth ratio, etc.). Given knowledge of parameter sensitivity, model prediction error and associated uncertainty were qualified as moderate- to highly-certain for the project. This is largely due to the fact that the most influential model input parameters were fairly well known (either directly measured or estimated in the field) while those that were relatively in-sensitive, were not. No other efforts were made to assess uncertainty as part of this project.

Table D-4. Summary of parameter sensitivity for the Big Hole River Heatsource v7.0 model.

Parameter	Rank	NSC
Ground temperature (ºC)	1	0.24
Air temperature (ºC)	2	0.21
Relative humidity (%)	3	0.12
Groundwater Q (cms)	4	0.07
Tributary Q (cms)	5	0.07
Groundwater temperature (ºC)	6	0.06
Wind speed (m/s)	7	0.04
Mass transfer “a” coefficient	8	0.03
Cloud cover (%)	9	0.03
Irrigation diversion (m/s)	10	0.03
Tributary temperature (ºC) Bankfull width (m) Headwater Q (cms) Manning’s “n” (dimensionless) Shade density (%) Width-depth ratio Channel z-angle (1:z) Headwater temperature (ºC) Particle size (mm) Muskingum “x” (dimensionless) Bed Ks (mm/s) Embeddedness (%)		<0.03

Model Calibration Procedure

The Big Hole River Heatsource v7.0 model was calibrated in an iterative fashion, from up- to downstream, based on the evaluation criteria identified previously. Generalized information related to model calibration can be found in Thomann (1982), James and Burges (1982), and ASTM (1984). Meteorological forcing data were first assessed as part of the calibration for artifacts of unrepresentative input data, e.g. where the model consistently has anomalous over- or under-prediction for only a portion of the simulation period. Cloud cover was the primary calibration parameter used in this instance. Additional calibration parameters included wind speed, groundwater accretion temperature, and Manning’s roughness coefficient. All were adjusted within a reasonable range such that agreement between observed and simulated values occurred. Final calibrated reach parameters are shown in Attachment-A. Subsequent PBIAS, NSE, and SSR values for the temperature calibration are described in the Results and Discussion section.

Model Validation/Confirmation

After calibration, a model should be validated or confirmed against an independent dataset. This effectively demonstrates that the model performs adequately over a range of conditions beyond that which it was calibrated to (Barthalow, 1989; Chapra and Reckow, 1983; Chapra, 1997). Unfortunately, independent data outside of the 2006 field effort do not exist for validation purposes largely due to the dynamic conditions encountered in the watershed. Therefore, several auxiliary lines of evidence were evaluated in a "low-level" confirmation exercise. This included: (1) an in-depth comparison of calculated physical subroutines in the model with that of field observations (e.g. hydrology, hydraulics, and shading discussed in subsequent sections) and (2) assessment of appropriate in-stream water temperature responses to varying climatic conditions.

RESULTS & DISCUSSION

Hydrology

Simulated streamflow for July 28th of the July 25-31, 2006 modeling period is shown in **fig. D-12**. Inspection of the observed and predicted values shows very good agreement. Hydrology is within ±5 percent at all monitoring nodes, and mean prediction PBIAS and standard error were +0.4 percent and 0.2 cms respectively (comparing daily simulated flow values with instantaneous field-measurements). Clearly, surface water hydrology is a function of the combined influence of tributary inflow, irrigation withdrawal and return flow, split channel flow (e.g. braiding), and localized groundwater accretion. Major surface water inflows occur in the Fishtrap, LaMarche, and Deep Creek and Wise River areas, and geological valley controls such as the Greenwood Bottoms, Maidenrock Canyon, and Notch Bottom provide substantial groundwater accretion. A large portion of the dewatering occurs in the lower reaches between Notch Bottom FAS and the High Road FAS near Twin Bridges.

In review of the water balance, little, if any, groundwater discharge to surface water occurs during the modeling period. This is consistent with the findings of Marvin and Voller (2000) who suggest that during the summer months, a majority of the irrigation losses from leaky ditches and flood irrigation are consumed by ET rather than returning to surface water through groundwater flow. Groundwater influx in the Big Hole River watershed does occur in two instances: (1) where large groundwater flow systems converge and intersect with the Big Hole alluvial aquifer, and (2) where geological valley controls contract the effective subsurface flow area causing pinching and localized expression of surface water. This influx is followed by immediate losses in the downstream direction as the valley expands. Both mechanisms of groundwater accretion/hyporheic exchange have been previously documented in the literature (Stanford and Ward, 1993; Ward et al., 1999; Malard et al; 1999). The regional alluvial aquifer convergence mentioned previously occurs in the Big Hole River near Fishtrap, LaMarche, and Deep Creeks (river km 132-122), near Wise River (km-102), and by Glen (km 68-58). Geological controls occur at Greenwood Bottom, Maiden Rock Canyon, and Notch Bottom (river km-88.5, 72.5, and 7.5 respectively).

Hydraulics

Correct simulation of river hydraulics ensures that the air-water interface and associated water column are exposed to an accurate duration of meteorological forcings within the model. A comparison of model hydraulics against measured field data for confirmation purposes is shown in **fig D-13**. In general, good agreement is seen between observed and simulated values. Mean PBIAS for computed channel velocities, wetted widths, and associated depths were -5.3 percent, 4.6 percent, and 19.9 percent respectively. Standard errors were and 0.08 m/s and 10 and 0.1 meters respectively. These are adequate given the gross simplification of channel geometry in Heatsource v.7.0 in contrast to more detailed hydraulic models.

Shade

Simulated stream shade includes shading from both topography and vegetation and integrates the effects of channel aspect, offset, and width at a particular model node. Stream shade predictions ranged from 1 to 36 percent at individual model nodes, and averaged 5.7 percent for the entire study reach. Overall simulation PBIAS was 3.5 percent with a standard error (in percent shade) of 4 percent. While this is not great, when compared to site specific observations taken with a solar pathfinder, model simulation values are within reason (**fig. D-14**). Modeled shade appears to track well with observed measurements and shows several distinct shading peaks occurring at river km-130, 80, and 50. These are a function of topography rather than vegetation, and correspond to topographic angles of greater than 10-degrees. Discrepancies between simulated and observed values exemplify the difference between measured point values and averages over the 1,000-m distance step.

Water Temperature

With concurrence between hydrology, hydraulics, and shade, it was expected that simulated water temperatures in Heatsource v7.0 would be in good agreement with observed values. Computed and observed minimum, mean, and maximum water temperatures for July 28th of the July 25-31, 2007 modeling period are shown in **fig. D-15**. Hourly diurnal plots are in **fig. D-16**. Overall, there is excellent agreement between both. In review of the calibration statistics, PBIAS was largely negligible (0.2 percent), hourly NSE was 0.88, SSQR = 51.49, and standard error = 0.6°C. Individual calibration statistics for modeling nodes are shown in **table D-5**.

Examination of the longitudinal profile of the Big Hole River provides significant information regarding in-stream water temperatures, and associated system dynamics. Beginning at the upstream boundary, temperature remains relatively constant until reaching Fishtrap, LaMarche and Deep Creeks. Significant cooling occurs, attenuates, and then occurs again near Wise River due to groundwater accretion and topographic shading. Much of the rest of the reach is characteristic of warming conditions. Temperatures reach 27°C (80.6°F) prior to reaching the confluence with the Beaverhead River.

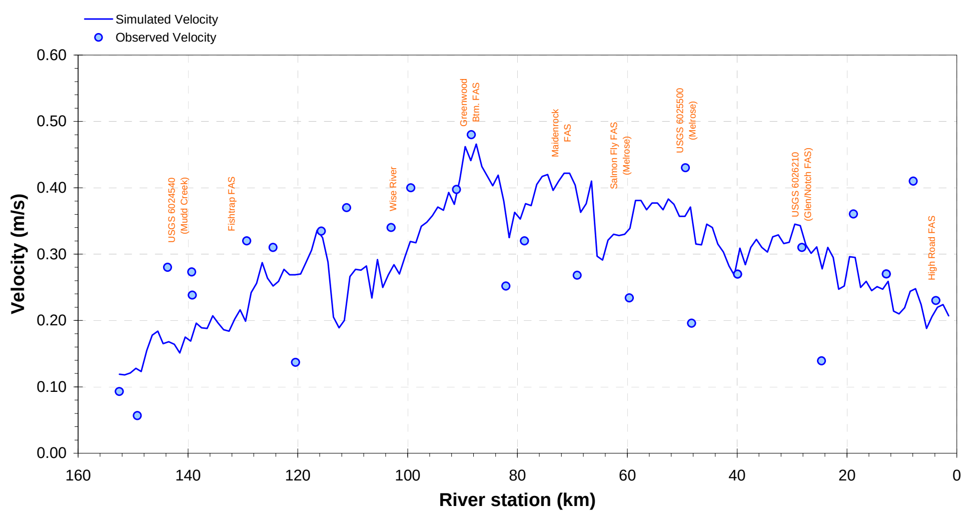
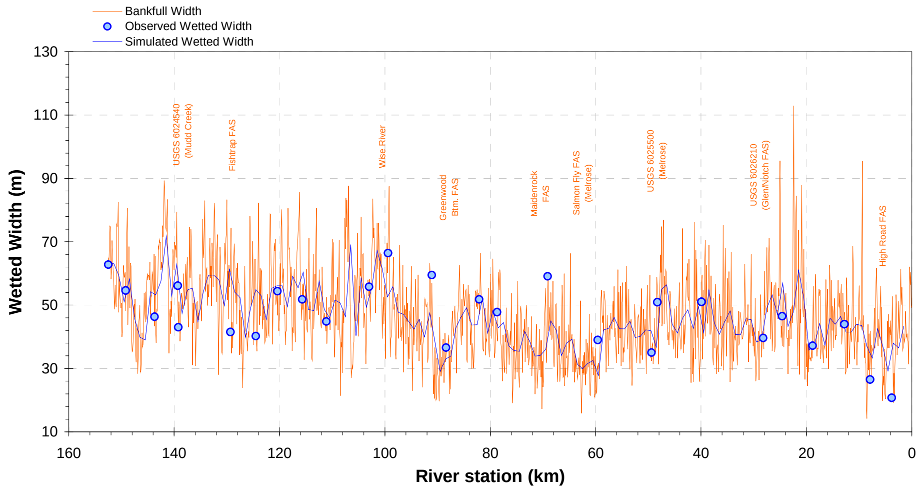
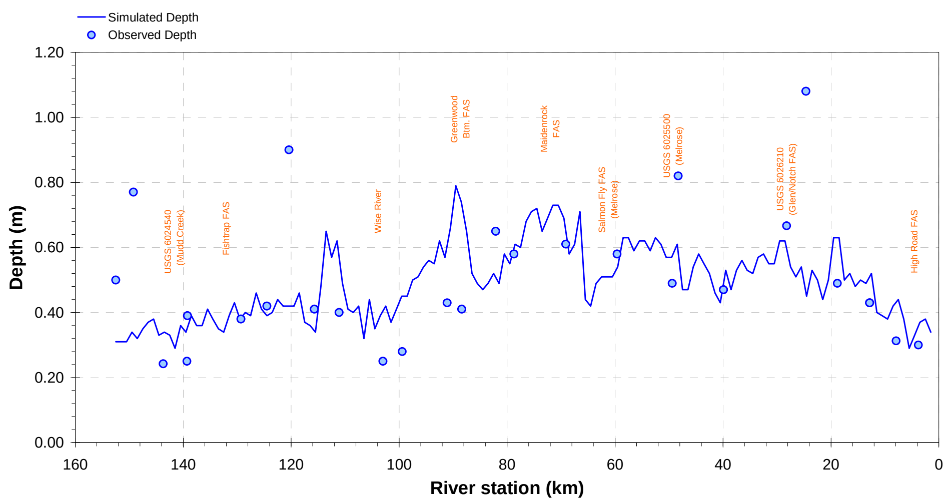


Figure D-12. Big Hole River simulated and observed hydrology for July 28th of the July 25-31, 2006 modeling period. Observed measurements were taken instantaneously over the 7-day study period and may not necessarily reflect conditions that day.

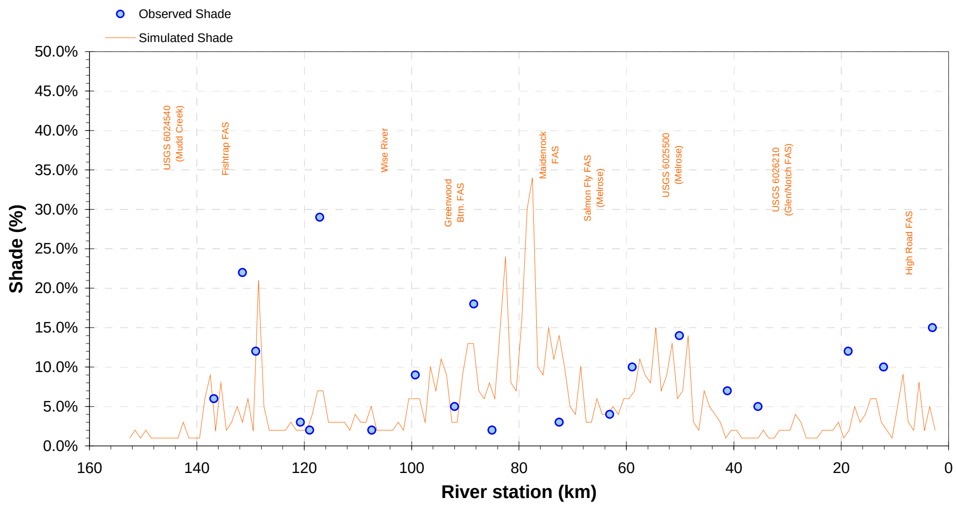
Figure D-13. Big Hole River simulated and observed hydraulics: a) mean velocity, b) mean wetted channel width, and c) mean hydraulic depth for July 28th of the July 25-31, 2006 modeling period. Observed measurements were taken instantaneously over the 7-day study period and may not necessarily reflect conditions that day.



a)



b)



c)

From further review of **fig. D-15**, the relationship between in-stream flow volume and associated water temperatures is apparent. As flows diminish, temperature increases. Rates of warming specifically increase in three instances: (1) in the upper reaches from low flow headwater conditions, (2) in several of the split flow locations due to a decrease in volume and increase in wetted surface area (e.g. river km 59.5 and 39.5), and (3) in the lower 40-km where much of the dewatering occurs. That said, the most heavily warmed sections are the upper and lower reaches. In both areas, temperatures exceed the UILT for Arctic Grayling (25ºC, 77ºF) and also are elevated above that which have been shown to cause the breakdown of physiological bodily processes for salmonid species (Boyd and Kasper, 2004). Fortunately, temperatures are moderated in center of the watershed by groundwater influx and shading, otherwise extremes in the lower watershed would be much more severe.

In calibration of surface water temperature (both the longitudinal profile and diurnal plots), groundwater accretion temperature was found to vary depending on the method of accretion. In areas where large alluvial groundwater systems converged, a temperature of 11°C (51.8°F) was used. This is consistent with temperatures reported by Marvin and Voller (2000) for groundwater in the Big Hole basin as well as those found in a 2007 query of the Groundwater Information Center (GWIC) database. In instances where both regional groundwater flow and geological controls occur, a temperature of 16°C (60.8°F) was used. For areas with consistent hyporheic exchange due to oxbowing and valley morphological controls, a temperature of 19°C (66.2°F) was used. Results are consistent with Boyd and Kasper (2004), Malard et al., (2001), Constantz and Thomas (1997), and Siliman and Booth (1993) who all indicate that shallow groundwater/hyporheic water temperatures are warmer than deep cold subsurface flows, and tend to be influenced by infiltrating stream water, thereby closely patterning diel surface water temperature fluctuations.

Overall, a very good surface water temperature calibration was achieved based on model statistical efficiency. Scenarios for TMDL planning and analysis are described in the following sections.

Table D-5. Hourly water temperature calibration statistics for July 25-31, 2006 modeling period.

Site ID	PBIAS	NSE	SSR	SE
RIVER KM – 139.2 (Z02)	-0.7%	0.91	45.73	0.7
RIVER KM – 129.3 (Z03)	-4.3%	0.82	116.83	0.6
RIVER KM – 124.5 (Z04)	-2.4%	0.87	75.06	0.7
RIVER KM – 115.7 (Z05)	-0.4%	0.91	47.97	0.7
RIVER KM – 111.1 (Z06)	2.3%	0.87	73.52	0.5
RIVER KM – 103.0 (Z22)	1.6%	0.84	92.38	1.0
RIVER KM – 99.4 (Z07)	1.8%	0.91	47.02	0.6
RIVER KM – 87.6 (Z46)	0.8%	0.79	57.85	0.8
RIVER KM – 82.1 (Z21)	0.6%	0.91	24.32	0.5
RIVER KM– 78.7 (Z08)	1.5%	0.90	27.91	0.5
RIVER KM – 69.1 (Z09)	1.7%	0.84	52.04	0.6
RIVER KM – 59.6 (Z10)	1.5%	0.86	52.48	0.7
RIVER KM – 49.4 (Z12)*	2.0%	0.86	46.80	0.6
RIVER KM – 39.9 (Z13)	1.4%	0.84	54.10	0.8
RIVER KM – 28.2 (Z14)*	-1.2%	0.93	22.11	0.4
RIVER KM – 18.8 (Z15)	-0.2%	0.93	22.37	0.5
RIVER KM – 12.8 (Z16)	-0.2%	0.91	28.05	0.6
RIVER KM – 07.9 (Z17)	-0.5%	0.88	40.69	0.6
RIVER KM – 03.7 (Z19)	-1.8%	0.91	51.01	0.7
AVG	0.2%	0.88	51.49	0.6

*Located at USGS gage sites

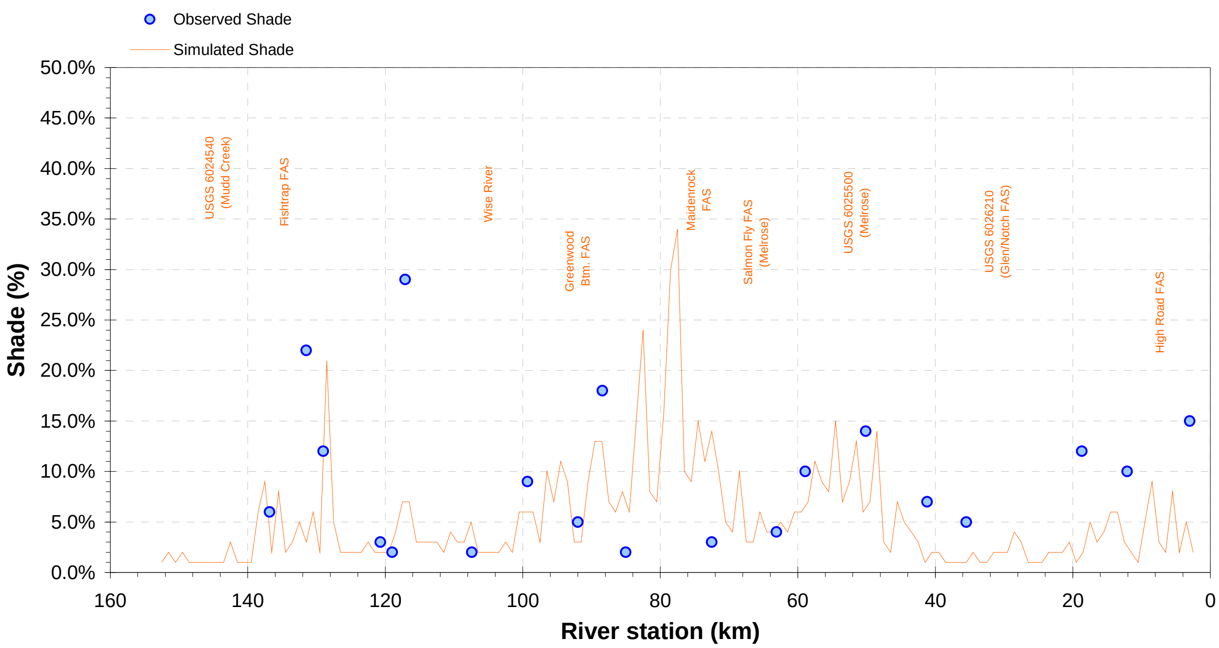


Figure D-14. Big Hole River simulated and observed shade for July 28th of the July 25-31, 2006 modeling period.

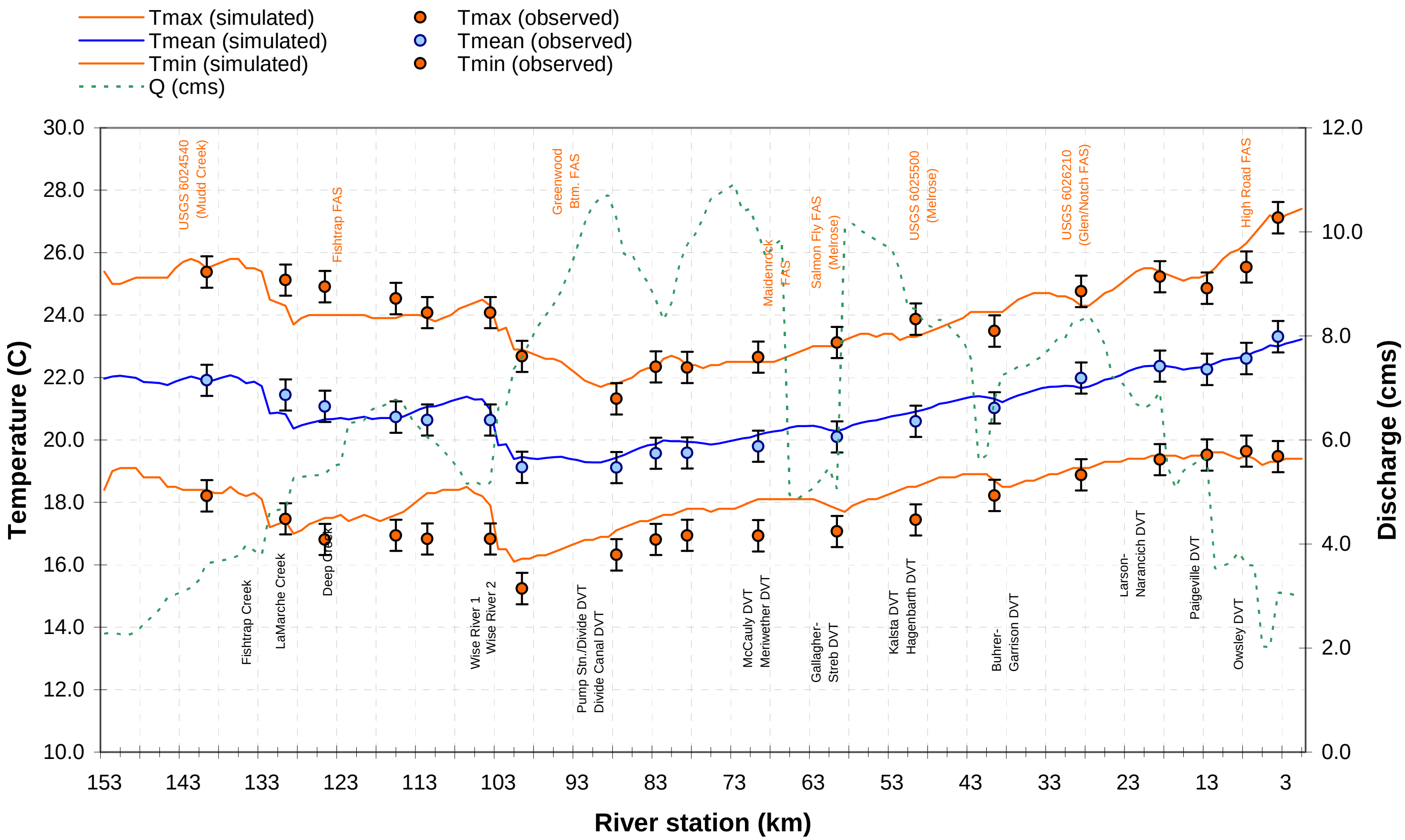
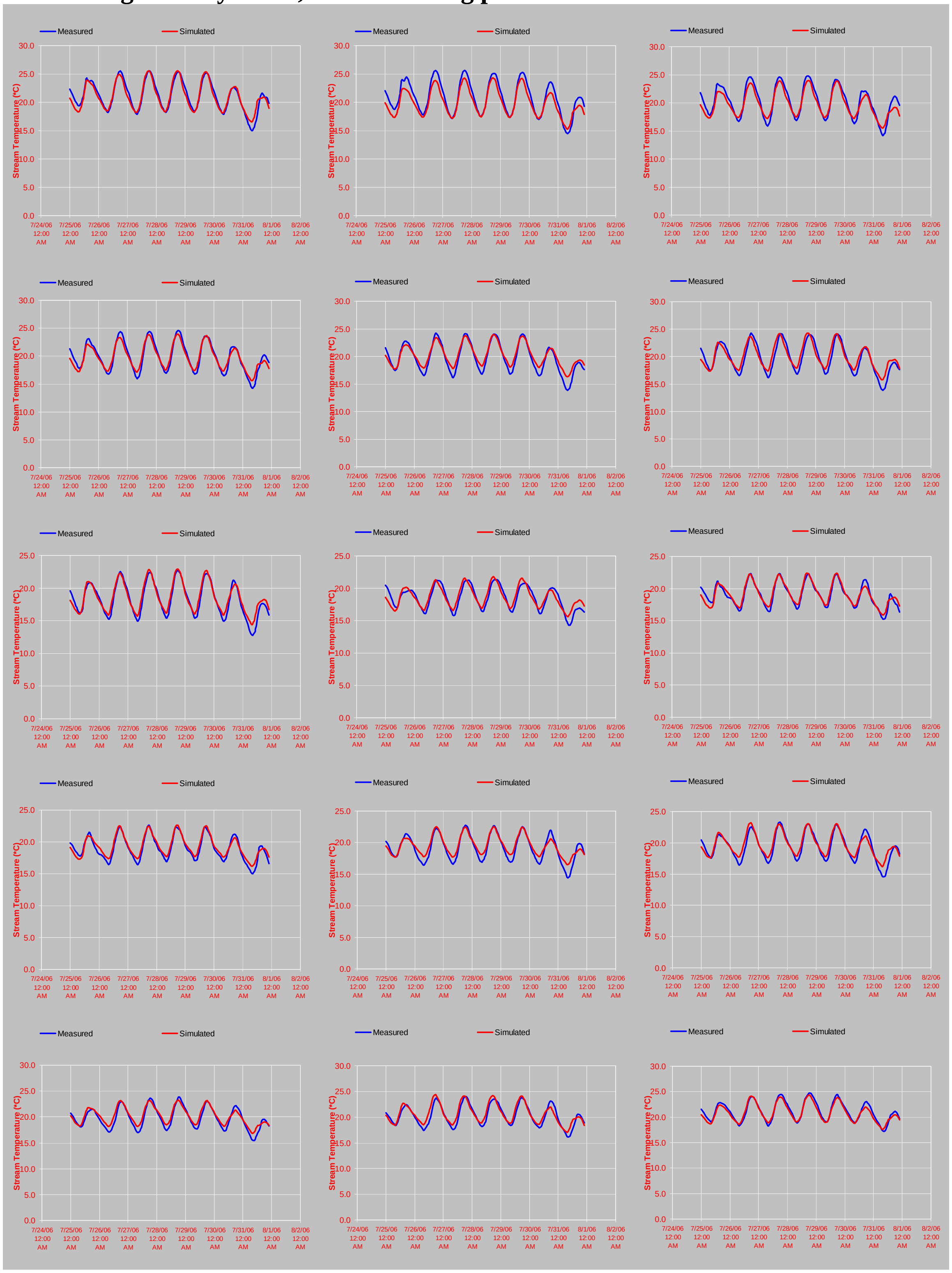
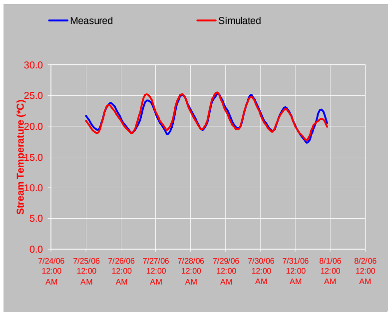
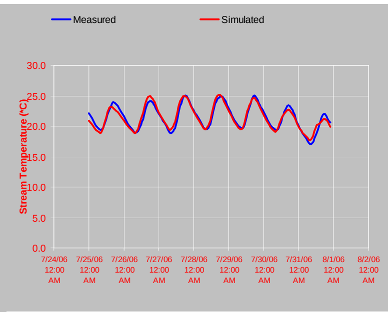


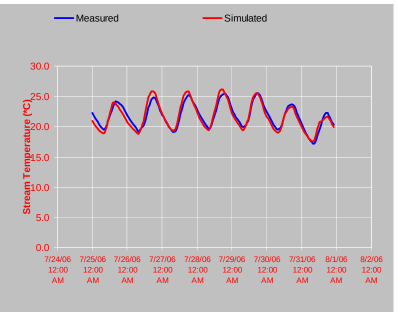
Figure D-15. Longitudinal temperature profile of the Big Hole River displaying Tmin, Tmax, Tavg, and mean discharge for July 28th of the July 25-31, 2006 modeling period. Error bounds of measured data (±0.2 ºC datalogger accuracy) are shown along with major inflows and outflows.

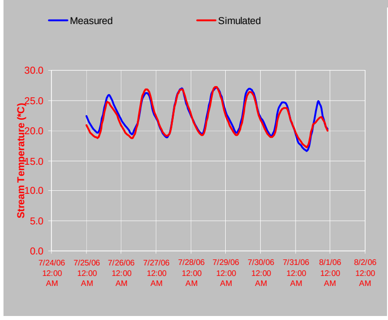
Figure D-16. Diurnal plots of observed and simulated temperature for the 19 monitoring stations on the Big Hole River during the July 25-31, 2006 modeling period.




Measured
Simulated
30.0
25.0
20.0
15.0
10.0
5.0
0.0
Stream Temperature (°C)
7/24/06 12:00 AM
7/25/06 12:00 AM
7/26/06 12:00 AM
7/27/06 12:00 AM
7/28/06 12:00 AM
7/29/06 12:00 AM
7/30/06 12:00 AM
7/31/06 12:00 AM
8/1/06 12:00 AM
8/2/06 12:00 AM


Measured
Simulated
30.0
25.0
20.0
15.0
10.0
5.0
0.0
Stream Temperature (°C)
7/24/06 12:00 AM
7/25/06 12:00 AM
7/26/06 12:00 AM
7/27/06 12:00 AM
7/28/06 12:00 AM
7/29/06 12:00 AM
7/30/06 12:00 AM
7/31/06 12:00 AM
8/1/06 12:00 AM
8/2/06 12:00 AM


Measured
Simulated
30.0
25.0
20.0
15.0
10.0
5.0
0.0
Stream Temperature (°C)
7/24/06 12:00 AM
7/25/06 12:00 AM
7/26/06 12:00 AM
7/27/06 12:00 AM
7/28/06 12:00 AM
7/29/06 12:00 AM
7/30/06 12:00 AM
7/31/06 12:00 AM
8/1/06 12:00 AM
8/2/06 12:00 AM


Measured
Simulated
30.0
25.0
20.0
15.0
10.0
5.0
0.0
Stream Temperature (°C)
7/24/06 12:00 AM
7/25/06 12:00 AM
7/26/06 12:00 AM
7/27/06 12:00 AM
7/28/06 12:00 AM
7/29/06 12:00 AM
7/30/06 12:00 AM
7/31/06 12:00 AM
8/1/06 12:00 AM
8/2/06 12:00 AM

SCENARIO ANALYSIS

A number of scenarios were developed as part of this study so that watershed managers can provide reasonable recommendations for meeting water quality criteria in the river. Vegetation losses from the riparian corridor, natural channel mophometry, and irrigation withdrawals have all been cited as causes for elevated water temperature in the Big Hole River (DEQ, 2004). However, little has been done to associate management activities in the river corridor with in-stream temperatures. Specifically, modeling scenarios were formulated to address the following: (1) baseline conditions, (2) a shade scenario in which reference shade is applied across the project reach, (3) a morphology scenario where channel mophometry is assumed to be under reference conditions, (4) water consumptive use scenario where effects of irrigation and domestic withdrawls are assessed, (5) a natural condition scenario with no anthropogenic influence, (6) naturally occurring scenario in which all reasonable land, soil, and water conservation practices are applied (ARM 17.30.602), and (7) a use attainment scenario where the model is applied toward a specific BMP for illustrative purposes.

Baseline Scenario

The baseline scenario describes existing conditions in the watershed and is merely a reflection of the calibration. In review, baseline modeling was completed during drought and in low flow conditions approaching the 7Q5. The simulation results have been documented in prior sections and indicate a very good water temperature calibration based on performance statistics of NSE, PBIAS, and SSR. Water temperature was shown to decrease from the upstream study limit to approximately Wise River, and then increase thereafter. Simulated values from the baseline scenario form the basis for which all other scenarios will be compared. For the rest of the document, temperature comparisons are reported as the 7-day minimum (7Dmin), 7-day average (7Davg), and 7-day maximum (7Dmax) water temperature.

Shade Scenario

During the field reconnaissance, the riparian corridor was characterized as being in good condition, with little observed disturbance. In order to exclude shade as a viable control on water temperature in the Big Hole River, a hypothetical shading scenario was run to characterize the maximum possible influence of shade on in-stream temperature. The following assumptions were made in the shade scenario: (1) all open/grassed sites, barren areas, and any other area with diminished shading vegetation was assumed to be converted to reference shade condition and (2) all other conditions were held constant. Reference shade was defined as the combination of 80 percent willow and 20 percent grass in the upper study reach (e.g. km 152.5-102.0) and a mix of 30 percent cottonwood gallery and 70 percent grass cover in the lower 102 km. The breakpoint for the vegetation change was Wise River, which is a clear demarcation in regard to hydrology, climate, and associated soils.

In addition to these changes, a secondary component was integrated into the modeling to assess the influence of upstream shading on the headwater boundary condition of Heatsource v7.0. A SSTEMP model from a previous study (DEQ, upper Big Hole River TMDL unpublished) was linked with Heatsource v7.0 so that the influence of upstream management activities could be propagated downstream. SSTEMP is single segment model that operates on a daily time step and computes many of the same heat flux components as Heatsource v7.0. In total, 94.5 km of river outside of the detailed study reach were evaluated. The model originated at the watershed headwaters and extended as far downstream as Pintlar Creek (e.g. upper TPA boundary). A zero flow headwater condition as described in Barthalow (1989) was used to calibrate SSTEMP water temperature to project hydrology and meteorology. Model assumptions for the SSTEMP shading scenario were as follows: (1) shade was assumed to be at reference condition in the upper TPA as identified by willow cover of height 4-m, crown of 1-m, density of 43%, and offset of 0.5-m (DEQ, upper Big Hole TMDL unpublished), and (2) all other conditions remained constant.

Baseline and simulated shade, along with associated in-stream water temperatures at the outlets of the upper and lower TPAs are shown in **table D-6** and **fig. D-17a**. Average shade in the upper TPA increased significantly, from 3.5 percent to 11.3 percent. Shade in the middle-lower TPA increased only 0.9 percent (5.7 percent to 6.6 percent). This translates into decreases of 0.38 and 0.82°C (0.68 and 1.48°F) in 7Dmin and 7Dmax at the upper TPA boundary while decreases of only 0.03 and 0.06°C (0.05 and 0.11°F) were observed at the watershed outlet near Twin Bridges (lower TPA). Clearly, shade is of great importance to localized conditions in the upper TPA (e.g. near the headwater boundary) but has little effect on the rest of the river. Standard violations were shown to extend 6-km into the detailed study reach, although these quickly attenuate as the river re-adjusts to meteorological and associated mass-transfers conditions in the Fishtrap Creek area. No other exceedances were observed in the middle or lower TPAs. Results strongly suggest that shade, while important to upper basin thermal dynamics, is not an integral component of the heat balance in the middle and lower Big Hole River TPAs. Thus shade improvement is not recommended as an alternative for temperature restoration strategies in the middle and lower basin. It should, however, be considered in the upper TPA to mitigate impairments near the upper detailed study reach boundary (e.g. first 6-km).

Table D-6. Temperature changes at end of simulation reach resulting from modification of shade on the Big Hole River (both SSTEMP and Heatsource v7.0 modeled segments).

Condition	% Shade	Tmin	Tavg	Tmax
Baseline (94.5-km)	3.5%	17.05	21.18	25.31
Shade Scenario	11.3%	16.67	20.58	24.49
Δ TEMP-Uppr TPA		-0.38	-0.60	-0.82
Baseline (152.5 km)	5.7%	18.93	22.17	25.59
Shade Scenario	6.6%	18.90	22.12	25.53
Δ TEMP-Lowr TPA		-0.03	-0.05	-0.06
Δ TEMP – all (1)		-0.04	-0.05	-0.05

(1)Average deviation of all model nodes, not just watershed outlet

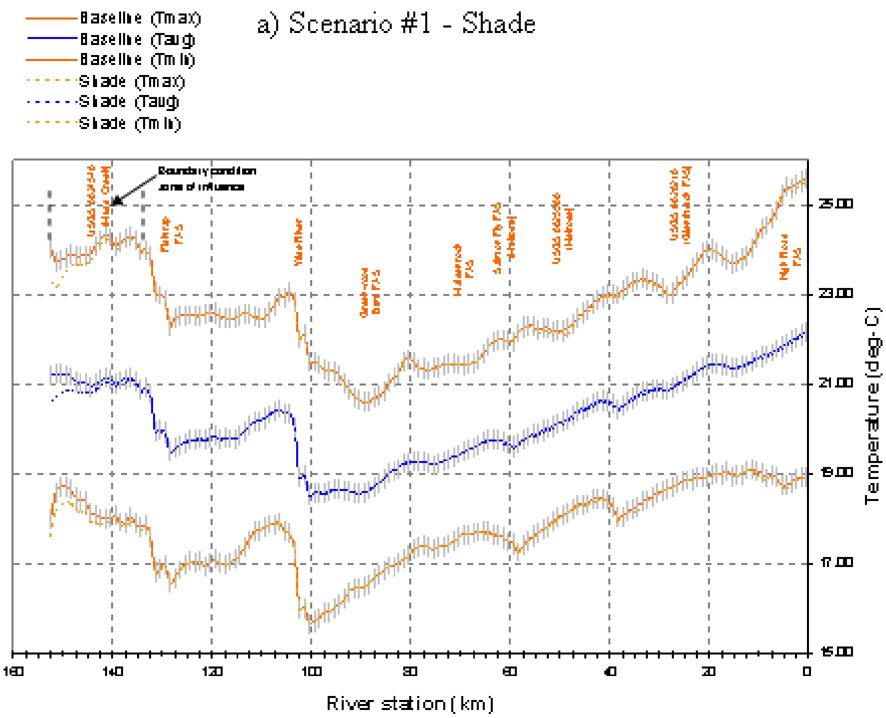
Channel Morphology Scenario

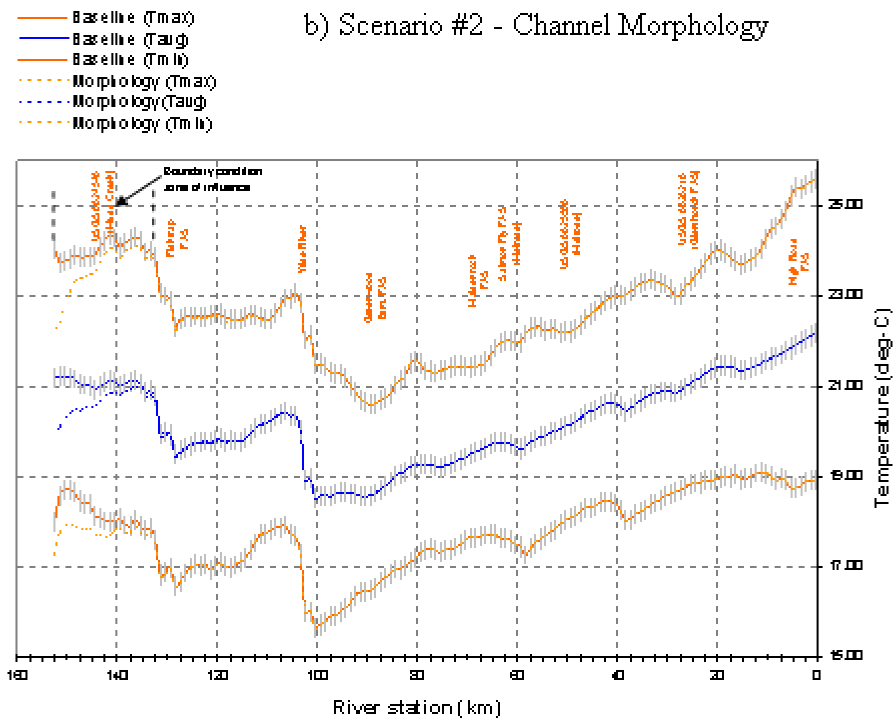
A channel morphology scenario was also completed to assess the influence of physical geometry on the overall heat balance of the reach. Similar to the shade scenario, both SSTEMP and Heatsource were used for this purpose. A coarse parameterization was completed to identify whether the wide reaches of the Big Hole River (width-depth ratios approaching 80 and 90) could potentially be altered to reduce the air-water interface, and subsequently, lower in-stream temperatures. Model parameterizations were formulated using targets from DEQ (upper Big Hole TMDL unpublished) and included the following assumptions: (1) width-depth ratios in the upper TPA were reduced by 30 percent, (2) width-depth ratios over 60 in the lower 152.5 km were set to 60, and (3) all other model parameters were held constant. Results of the SSTEMP model runs show that substantial reductions (up to 1.79°C; 3.22°F in 7Dmax) can be achieved at upstream end of the project reach (**table D-7**). This effect quickly reverts back toward baseline though as the water column is subjected to prolonged exposure of atmospheric conditions (**fig. D-17b**). Because changes are short lived, and do not propagate into the heavily warmed lower sections of the river, morphology modification is not recommended as suitable mechanism for controlling in-stream temperatures in the lower Big Hole River TPA. It does remain a viable option upstream of Pintlar Creek.

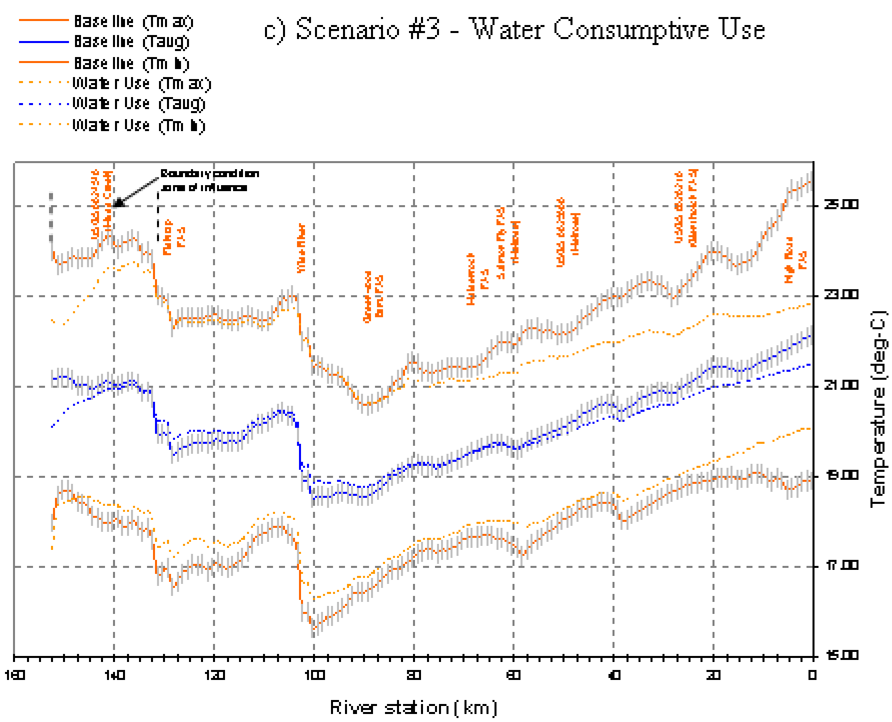
Table D-7. Temperature changes at end of simulation reach resulting from modification of river morphology of the Big Hole River (both SSTEMP and Heatsource v7.0 modeled segments).

Condition	W-D Ratio	Tmin	Tavg	Tmax
Baseline (94.5-km)	35	17.05	21.18	25.31
Morph Scenario	25	16.34	19.86	23.38
Δ TEMP-Pintlar Cr		-0.71	-1.32	-1.93
Baseline (152.5 km)	>60	18.93	22.17	25.59
Morph Scenario	≤60	18.93	22.16	25.57
Δ TEMP-Twin Br		0.00	-0.01	-0.02
Δ TEMP – all		-0.06	-0.07	-0.07

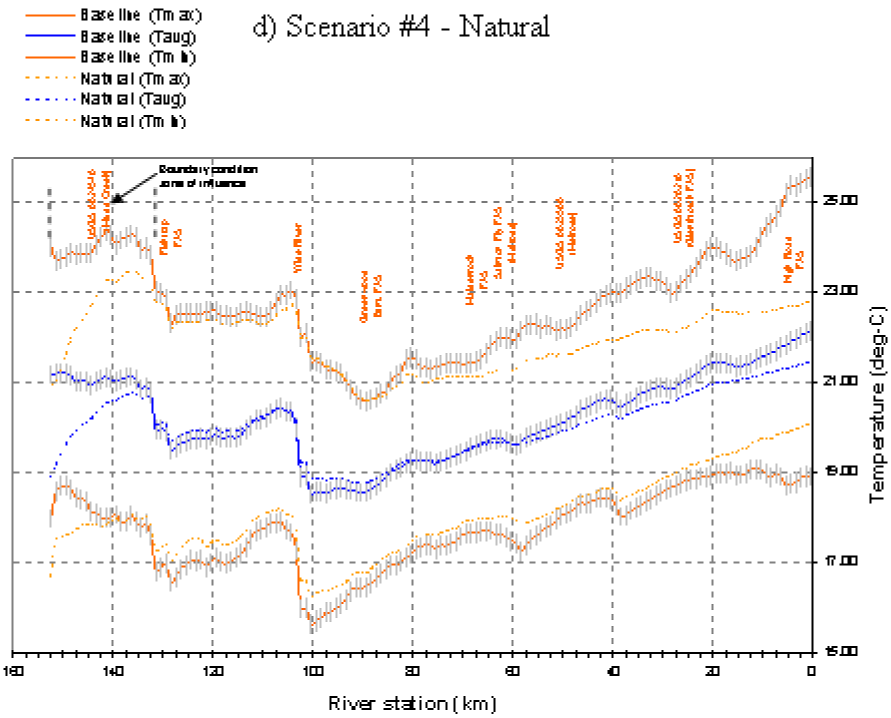
Figure D-17. Longitudinal temperature effects of management scenarios on the Big Hole River. The grey shaded area represents ±0.23ºC degree variation from that of baseline conditions. Scenarios that deviate outside the 0.23ºC boundary indicate potential impairment.



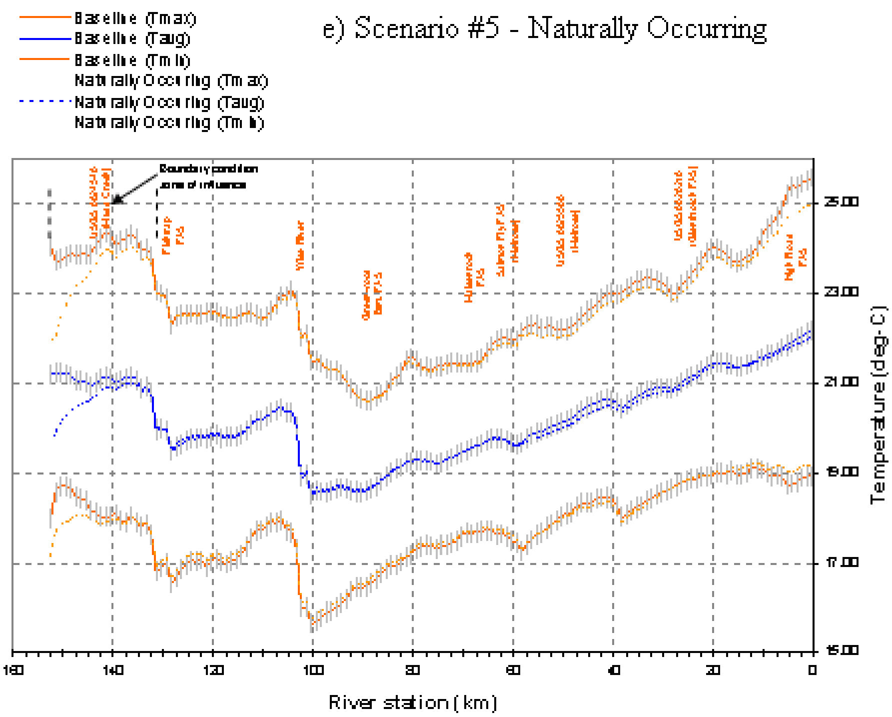

b) Scenario #2 - Channel Morphology
Baseline (Tmax)
Baseline (Taug)
Baseline (Tmin)
Morphology (Tmax)
Morphology (Taug)
Morphology (Tmin)
Boundary condition zone of influence
River station (km)
Temperature (deg-C)

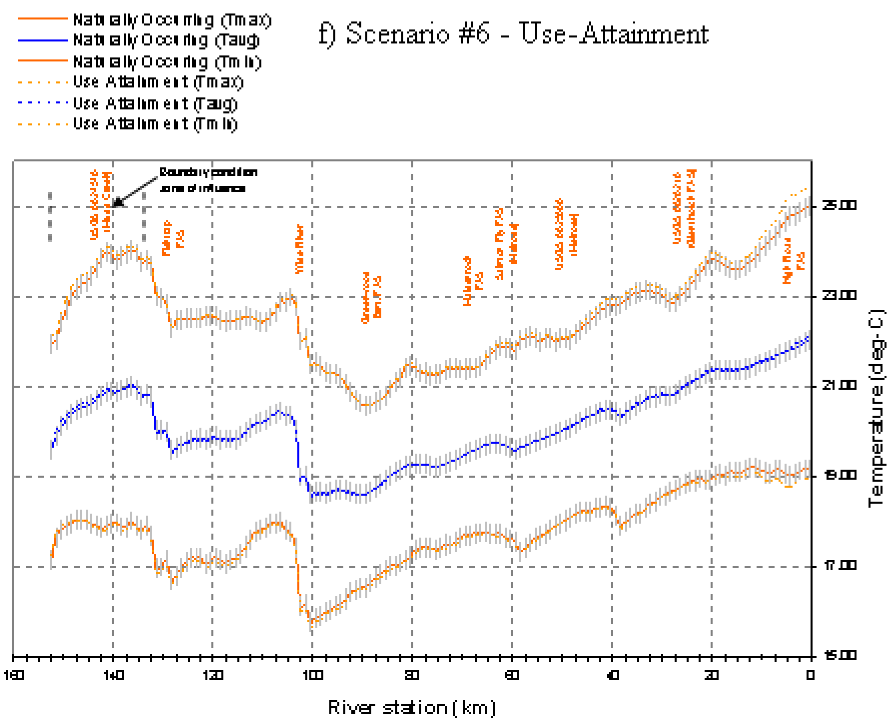

c) Scenario #3 - Water Consumptive Use
Baseline (Tmax)
Baseline (Taug)
Baseline (Tmin)
Water Use (Tmax)
Water Use (Taug)
Water Use (Tmin)
Boundary condition zone of influence
River station (km)
Temperature (deg-C)

d) Scenario #4 - Natural



e) Scenario #5 - Naturally Occurring



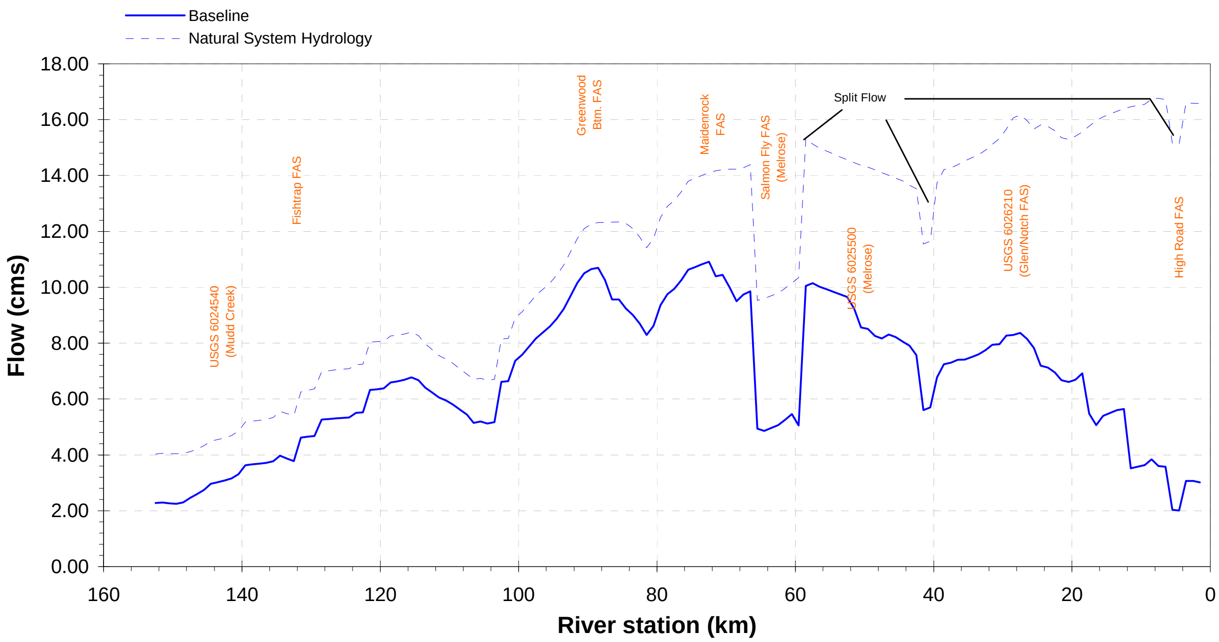


Water Consumptive Use Scenario

The water consumptive use scenario describes the thermal effect of irrigation and domestic water use on the Big Hole River. Although Montana standards do not necessarily apply to consumptive water use, it is important to assess the cumulative effect of these practices on the overall thermal regime of the river. The simple relationship presented by Brown (1969) suggests that large volume streams are less responsive to temperature changes, and conversely, low flow streams will exhibit greater diel fluctuations in stream temperature. The following assumptions were made in the water consumptive use scenario: (1) 1.75 cms (~60 cfs) of natural flow were returned upstream of the detailed study reach along with a corresponding change in temperature, (2) all diversions were removed from the detailed study along with any known return flows, and (3) no additional changes were made.

Overall, it was identified that 13.267 cms (~469 cfs) was diverted from the river during July 25-31 2006 to meet water use requirements in the middle and lower TPA's (**fig. D-18**; see **Appendix-A**). Withdrawl rates are slightly higher than those reported by Wells and Decker-Hess (1981) who indicate up to 9.29 cms (328 cfs) was removed from the river during the summer of 1980, as well as Marvin and Voller (2000) who estimate crop ET alone at 4.9 cms (171 cfs) in the lower basin. With unknown losses in the distribution system, and unaccounted ET in the middle basin, it is very reasonable to assume water withdrawls routinely approximate 9-13 cms in the late summer months. During 2006, all but 0.439 cms were used for agricultural purposes.

Figure D-18. Longitudinal profile of discharge in the watershed as part of the water use scenario. The 1.75 m3/s headwater increase is included in this approximation along with removal of all diversions in the study area.



Model simulations of natural system hydrology indicate that significant changes in temperature occur at the upstream boundary and watershed outlet from irrigation and domestic water withdrawls **(table D-8, fig. D-17c**). 7Davg and 7Dmax are shown to decrease by 0.65 and 2.73°C (1.17 and 4.91°F), while 7Dmin actually increases as due to additional system volume, its associated thermal inertia, and the relative change in the ratio of contribution of groundwater to surface water. Interestingly, water temperatures largely "reset" in the area around Wise River. This phenomena was also observed in other scenarios and is suggestive that basin could be broken into two independent management segments with independent remedial objectives. Clearly, flow augmentation in the Big Hole River is a crucial improvement necessary for modification of in-stream water temperature in the middle and lower TPA's.

Table D-8. Temperature changes at end of simulation reach resulting from modification of consumptive use on the Big Hole River (both SSTEMP and Heatsource v7.0 modeled segments).

Condition	Q (cms)	Tmin	Tavg	Tmax
Baseline (94.5 km)	3.135	17.05	21.18	25.31
Water Scenario	4.885	16.53	20.08	23.63
Δ TEMP-Pintlar Cr	1.75	-0.52	-1.10	-1.68
Baseline (152.5 km)	3.022	18.93	22.17	25.59
Water Scenario	16.579	20.09	21.52	22.86
Δ TEMP-Twin Br		+1.16	-0.65	-2.73
Δ TEMP – all		+0.41	-0.09	-0.66

Natural Condition Scenario

The natural condition scenario reflects the temperature regime that would be expected absent of the influence of man. While this type of scenario is clearly not realistic from a socio-economic implementation standpoint, it does allow for characterizing the extent of departure from natural conditions, and subsequently, the maximum potential improvement in the watershed. It may also be helpful in future resource conservation efforts. For the purpose of this study, natural conditions were defined as the removal of all human influences that affect heat or mass transfer. Natural condition scenario assumptions include the following: (1) reference shade conditions as described in the shade scenario, (2) modified morphology in the 94.5 km reach upstream and constant channel morphology downstream, (3) the same irrigation and consumptive use conditions as in the water consumptive use scenario, and (4) no other associated changes.

Results of the natural condition scenario parallel that of the previous scenario (e.g. water consumptive use) with 7Davg and 7Dmax decreasing by 0.69 to 2.76°C (1.24 and 4.97°F) and 7Dmin increasing (**table D-9**). The marked concurrence between the natural condition and water use scenarios confirm that irrigation and domestic withdrawls are the predominant impairment affecting the Big Hole River; much more so than that of shade and morphology. The natural condition profile is shown in **fig. D-17d**.

Table 9. Temperature changes at end of simulation reach resulting from natural conditions on the Big Hole River (both SSTEMP and Heatsource v7.0 modeled segments).

Condition		Tmin	Tavg	Tmax
Baseline (94.5 km)		17.05	21.18	25.31
Natural Scenario		15.83	18.90	21.97
Δ TEMP-Pintlar Cr		-1.22	-2.28	-3.34
Baseline (152.5 km)		18.93	22.17	25.59
Natural Scenario		20.07	21.48	22.83
Δ TEMP-Twin Br		+1.14	-0.69	-2.76
Δ TEMP – all		+0.30	-0.20	-0.77

Naturally Occurring Scenario (ARM 17.30.602)

The naturally occurring scenario defines water temperature conditions resulting from the implementation of all reasonable land, soil, and water conservation practices (LSWCP), e.g. where stringent best management practices are implemented as outlined in ARM 17.30.602. Essentially, “naturally occurring” establishes the bar for which the allowable 0.23°C (0.5°F) temperature increase is compared to, and effectively determines the impairments status of a water body. Assumptions used in the development of the naturally occurring scenario include the following: (1) identical shade conditions to those described in the shade scenario, (2) modified morphology in the 94.5 km reach upstream, (3) constant channel morphology downstream, (4) a 15 percent (0.5cms) irrigation efficiency improvement in the upper TPA (per DEQ and DNRC estimates), (5) a 15 percent irrigation/domestic water use efficient in the middle and lower TPAs (DEQ estimated), and (6) no other associated changes.

Results of the naturally occurring scenario suggest that 7Davg and 7Dmax would be reduced by 0.13 and 0.59°C (0.23 and 1.06ºF), respectively, while nighttime minimums would increase by 0.26°C (**table**

D-10 and **fig D-17e**). As such, a majority of the river in its current form already meets the State of the Montana temperature standard (e.g. within the 0.23°C allowable increase). Standard violations in 7Dmax do occur in three locations: (1) in the upper reaches as a result of upstream management conditions (river km-152.5-135.5), (2) at river km-55.5 between Melrose and Glen from heavy irrigation and domestic withdrawal, and (3) from river km-10.5 dowstream due to cumulative effects of dewatering. Management activities should be prioritized to address these most impacted sections first, while then worrying about other areas of the river later.

Table D-10. Temperature changes at end of simulation reach resulting from naturally occurring conditions on the Big (both SSTEMP and Heatsource v7.0 modeled segments).

Condition		Tmin	Tavg	Tmax
Baseline (94.5 km)		17.05	21.18	25.31
Naturally Scenario		16.24	19.65	23.06
Δ TEMP-Pintlar Cr		-0.81	-1.53	-2.25
Baseline (152.5 km)		18.93	22.17	25.59
Naturally Scenario		19.19	22.04	25.00
Δ TEMP-Twin Br		+0.26	-0.13	-0.59
Δ TEMP – all		+0.01	-0.09	-0.19

Use Attainment Scenario

A final scenario was developed to illustrate the utility of the Heatsource v7.0 model for future application in the Big Hole River. In this hypothetical scenario, the hypothesis was formulated that 10 percent irrigation efficiency (as opposed to 15 percent, all other factors the same) would be sufficient to meet the State temperature standard. The hypothesis was tested using identical assumptions to that of the naturally occurring scenario, with the exception of the change in flow. Results indicate that for the most part, 10 percent irrigation efficiency would meet allowable increases by State law. Exceedances did occur, however, in the lower watershed, largely disproving the hypothesis (**fig. D-17d**). Therefore, the next step would be to develop a new set of assumptions (perhaps something like a 10 percent efficiency improvement the upper reaches and 15 percent in the lower reaches) as a subsequent test to assess whether water quality standards can be met. Ultimately, the goal would be to identify a suite of BMPs that are agreeable between watershed stakeholders and managers such that the Montana temperature standard is attained and maintained. This, of course, would require cooperative efforts between landowners, watershed groups, managers, modelers, and the general public. For the time being, a watershed-wide 15 percent improvement in flow, along with shading improvement in the upper, middle, and lower TPA's, and morphology improvements in the upper TPA, are recommended to meet the state temperature standard.

CONCLUSION

Water temperature modeling was completed on the Big Hole River using Heatsource v7.0 and SSTEMP such that the mechanistic relationship between in-stream water temperature, stream morphology, riparian conditions, and water management practices could be established for the summer critical low-flow period. Through scenario analysis, it was shown that flow alteration was the most crucial management component influencing water temperature in the basin and that existing water temperatures are 0.59ºC (1.06ºF) warmer than that of naturally occurring conditions. They are 2.76ºC (4.97ºF) higher than natural. Thus the key management recommendation originating from this study is to protect and reestablish in-stream flows to the extent possible.

It was found during the modeling, that much of the middle and lower Big Hole River TPAs already meet the State's temperature criteria. Three areas of concern do exist: (1) in the reaches upstream of Fishtrap Creek/FAS as a result of management conditions in the upper TPA, (2) at river km-55.5 between Melrose and Glen from heavy irrigation and domestic water withdrawal, and (3) from approximately river km-10.5 downstream to Twin Bridges due to cumulative effects of dewatering. It was found that voluntary water conservation of 15 percent would be necessary to meet the state temperature standard in those reaches. Further modeling is recommended such that specific BMPs can be established cooperatively between stakeholders and watershed managers to refine this 15 percent estimate.

Finally, a unique "resetting" condition was identified near the center of the watershed where significant groundwater influx and topographic shading result a thermal buffering of in-stream water temperatures. This functionally separates the upper and middle/lower Big Hole River TMDL planning areas and would allow for future management of the river in two distinct segments.

REFERENCES

ARM 17.30.623 (Administrative Rules of Montana). Section 17 – Water Quality, B-1 Classification Standards. Accessed October 9, 2007 from http://arm.sos.mt.gov/17/17-2715.htm.

Anderson, R.L. 1982. Conflict Between Establishment of Instream Flows and Other Water Uses on Western Streams. Journal of the American Water Resources Association 18 (1), 61–65.

ASTM (American Society for Testing and Materials). 1984. Standard Practice for Evaluating Environmental Fate Models of Chemicals. Designation E978-84. Philadelphia, PA. 8 p.

Bahls, L. 1978. Streamflow and Water Quality in the Lower Big Hole River Summer 1977. Agency Report. Montana Department of Health and Environmental Sciences.

Bartholow, J.M., 1989. Stream Temperature Investigations: Field and Analytic Methods. Instream Flow Information Paper No. 13. U.S. Fish Wildlife Service Biological Report. 89(17). 139 pp.

BHWC (Big Hole River Watershed Committee). 1999. Big Hole River Drought Management Plan.

Brown, G.W. 1969. Predicting temperatures of small streams. Water Resources Research. 5(1) p. 68-75.

Bundschuh, J. 1993. Modeling annual variations of spring and groundwater temperatures asscociated with shallow aquifer systems. J. Hydrol. 142: 427-444.

Chapra, S.C. 1997. Surface Water Quality Modeling. McGraw-Hill Companies, Inc., New York.

Chapra, S.C. and K.H. Reckow. 1983. Engineering Approaches For Lake Management. Vol. 2: Mechanistic Modeling. Butterworth Publishers, Boston.

Constantz, J., and C.L. Thomas. 1997. Stream bed temperature profiles as indicators of percolation characteristics beneath arroyos in the middle Rio Grande Basin, USA. Hydrol. Processes. 11: 1621-1634.

CWAIC (Clean Water Act Information Center). Accessed October 9, 2007 from Montana Department of Environmental Quality. http://www.deq.state.mt.us/ CWAIC/default.aspx.

Deer Lodge County Water Resources Survey (WRS). 1955. Part I: History of the Land and Water use on Irrigated Areas and Part II: Maps showing irrigated areas in color sesignating the sources of supply. State Engineer's Office. Helena, MT.

Diskin, M.H. and Simon, E. (1977). "A procedure for the selection of objective functions for hydrologic simulation models." Journal of Hydrology, 34, 129-149.

FWP (Montana Fish, Wildlife, and Parks), 1989. Application for reservations of water in the Missouri River basin above Fort Peck Dam, Volume 2. June 1989. Upper Missouri instream flow studies Contract No. MT950-CTO-36.

Gammons, C., Ridenour, R. and A. Wenz. 2001. Diurnal and Longitudinal Variations in Water Quality on the Big Hole River and Tributaries During the Drought of August, 2000. Montana Bureau of Mines and Geology Open File Report 424.

Harmel, R.D., Cooper, R.J., Slade, R.M., Haney, R.L., and J.G. Arnold. 2006. Cumulative uncertainty in measured streamflow and water quality data for small watersheds. Transactions of the ASABE. Vol. 49(3): 689-701.

James, L.D. and S.J. Burges. 1982. Selection, Calibration, and Testing of Hydrologic Models. In: Hydrologic Modeling of Small Watersheds. ASAE Monograph No. 5. C.T. Haan, H.P. Johnson,

D. L. Brakensiak (eds). American Society of Agricultural Engineers, St Joseph, MI. Chap 11. pp 437-474.

Levings, J.F., 1986. Water resources of the Big Hole basin, southwestern Montana: Montana Bureau of Mines and Geology, Memoir 59, 72 p.

Lohr, S.C., P.A. Byorth, C.M. Kay, and W.P. Dwyer. 1996. High-temperature tolerances of Fluvial Arctic Grayling and comparison with summer river temperatures of the Big Hole River, Montana. Transactions of the American Fisheries Society 125:933-939.Magee and Lamothe (2003, 2004)

Magee, J.P. and P.J. Lamothe. 2003. Big Hole River Arctic grayling recovery project: Annual monitoring report 2002. Submitted to: Fluvial Arctic Grayling Workgroup. Montana Fish, Wildlife, and Parks, Bozeman, Montana

Magee, J.P. and P.J. Lamothe. 2004. Fluvial Arctic grayling monitoring report 2003. Submitted to: Fluvial Arctic Grayling Workgroup. Montana Fish, Wildlife, and Parks, Bozeman, Montana.

Magee, J., Rens, E., and P. Lamothe. 2006. Arctic Grayling Recovery Program: Montana Arctic Grayling Monitoring Report 2005. Montana Department of Fish, Wildlife and Parks. Dillon, Montana.

Malard, F., Mangin, A., Uehlinger, U. and J.V. Ward. 2001. Thermal heterogeneity in the hyporheic zone of a glacial floodplain. Can. JU. Fish. Aquat. Scie. 58: 1319-1335.

Marvin, R. K. 1997. Ground-water/surface-water interactions in the upper Big Hole basin, Montana: Montana Bureau of Mines and Geology open-file report 349. 58 p.

Marvin, R.K., and Voeller, T.L. 2000. Hydrology of the Big Hole Basin and an assessment of the affects of irrigation of the hydrologic budget. Montana Bureau of Mines and Geology Open File Report 417. Montana Bureau of Mines and Geology, Butte, Montana.

McCarthy, P.M., 2005, Statistical summaries of streamflow in Montana and adjacent areas, water years 1900 through 2002: U.S. Geological Survey Scientific Investigations Report 2004-5266, 317 p.

DEQ (Montana Department of Environmental Quality)., 2007. QA/QC of datalogger recovery for Big Hole River. DEQ monitoring program.

DEQ/Watershed Consulting. 2006. Quality Assurance Project Plan and Sampling and Analysis Plan for Big Hole River.

DEQ. Monitoring Guidance. Accessed May 15, 2006 from http://www.deq.state.mt.us/wqinfo/monitoring/ SOP/pdf/11-04.pdf

DEQ (Montana Department of Environmental Quality). 2004. Watershed Characterization Report – Middle and Lower Big Hole Water Quality Restoration Planning Areas. Prepared by Land and Water Consulting.

MFISH (Montana Fisheries Information System). Accessed October 9, 2007 from http://maps2.nris.mt.gov/scripts/esrimap.dll?name=MFISH&Cmd=INST&WCmd=Stream.

Montana Code Annotated. 2003. Montana Water Quality Act. Title 75. Environmental Protection Chapter 5. Water Quality.

MRA (Montana River Action) website. Accessed May 9, 2007 from http://www.montanariveraction.org.html

Nash, J.E., and V. Sutcliffe, 1970: River flow forecasting through conceptual models, I. A discussion of principles. Journal of Hydrology. 10: 282-290.

Phillip, A. 1999. A chemical study of irrigation and return flow waters in the Big Hole River basin of southwest Montana: Montana Tech – University of Montana M.S. thesis, 104 p.

Pimentel, D., Houser, J., Preiss, E., White, O., Fang, H., Mesnick, L., Barsky, T., Tariche, S., Schreck, J., and S. Alpert, 1997. Water Resources: Agriculture, Environment, and Society. BioScience, Vol. 47, No. 2. pp. 97-106.

Pringle, C. M. 2000. Threats to U.S. public lands from cumulative hydrologic alterations outside of their boundaries. Ecological Applications Vol. 10, No.4. pp. 971-989.

Rens, E.. and J. Magee. 2007. Arctic Grayling Recovery Program: Montana Arctic Grayling Monitoring Report 2006. Montana Department of Fish, Wildlife and Parks. Dillon, Montana.

Thomann, R.V. 1982. Verification of Water Quality Models. Jour. Env. Engineering Div. (EED) Proc. ASCE, 108:EE5, October.

Thomas, J.L. and R.L. Anderson. 1976. Water-energy conflicts in Montana's Yellowstone River Basin. Water Resources Bulletin. Vol. 12, No. 4.

Troxler, R.W., and E. L. Thackston, 1975. Effect of Meteorological Variables on Temperature Changes in Flowing Streams. Ecological Research Series EPA-660/3-75-002.

Siliman, S.E., Ramirez, J., and R.L. McCabe. 1995. Quantifying downflow through creek sediments using temperature series: one-dimensional solution incorporating measured surface temperature. J. Hydrol. 167: 99-119.

Van Liew, M.W., Arnold, J.G., and D.D. Bosch. 2005. Problems and Potential of Autocalibrating a Hydrologic Model. Transactions of the ASCE. Vol. 48(3): 1025-1040.

Ward, J.V., Malard, F., tockner, K. and U. Uehligner. 1999. Influence of groundwater on surface water conditions in a glacial flood plain of the Swiss Alps.Hydrol. Process. 13: 277-293.

Wells, J.D. and J. Decker-Hess. 1981. Inventory and survey of the waters of the Big Hole and Beaverhead drainages, July 1, 1980 through June 1, 1981. Southwest Montana fisheries study.

WRCC (Western Regional Climate Center). Accessed October 9, 2007 from http://www.wrcc.dri.edu.

USACE (United States Army Corps of Engineers). 1993. Engineering and Design - River Hydraulics. EM 1110-2-1416. 15 October 1993.